

**CIGR Handbook
of Agricultural Engineering
Volume IV**

CIGR Handbook of Agricultural Engineering

Volume IV Agro-Processing Engineering

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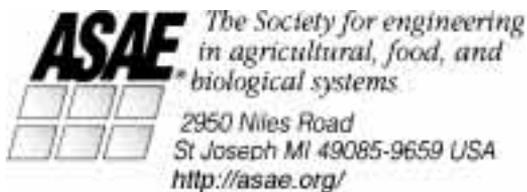
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Foreword

This handbook has been edited and published as a contribution to world agriculture at present as well as for the coming century. More than half of the world's population is engaged in agriculture to meet total world food demand. In developed countries, the economic weight of agriculture has been decreasing. However, a global view indicates that agriculture is still the largest industry and will remain so in the coming century.

Agriculture is one of the few industries that creates resources continuously from nature in a sustainable way because it creates organic matter and its derivatives by utilizing solar energy and other material cycles in nature. Continuity or sustainability is the very basis for securing global prosperity over many generations—the common objective of humankind.

Agricultural engineering has been applying scientific principles for the optimal conversion of natural resources into agricultural land, machinery, structure, processes, and systems for the benefit of man. Machinery, for example, multiplies the tiny power (about 0.07 kW) of a farmer into the 70 kW power of a tractor which makes possible the production of food several hundred times more than what a farmer can produce manually. Processing technology reduces food loss and adds much more nutritional values to agricultural products than they originally had.

The role of agricultural engineering is increasing with the dawning of a new century. Agriculture will have to supply not only food, but also other materials such as bio-fuels, organic feedstocks for secondary industries of destruction, and even medical ingredients. Furthermore, new agricultural technology is also expected to help *reduce* environmental destruction.

This handbook is designed to cover the major fields of agricultural engineering such as soil and water, machinery and its management, farm structures and processing agricultural, as well as other emerging fields. Information on technology for rural planning and farming systems, aquaculture, environmental technology for plant and animal production, energy and biomass engineering is also incorporated in this handbook. These emerging technologies will play more and more important roles in the future as both traditional and new technologies are used to supply food for an increasing world population and to manage decreasing fossil resources. Agricultural technologies are especially important in developing regions of the world where the demand for food and feedstocks will need boosting in parallel with the population growth and the rise of living standards.

It is not easy to cover all of the important topics in agricultural engineering in a limited number of pages. We regretfully had to drop some topics during the planning and editorial processes. There will be other requests from the readers in due course. We would like to make a continuous effort to improve the contents of the handbook and, in the near future, to issue the next edition.

This handbook will be useful to many agricultural engineers and students as well as to those who are working in relevant fields. It is my sincere desire that this handbook will be used worldwide to promote agricultural production and related industrial activities.

Osamu Kitani
Editor-in-Chief

Preface

Agro-processing engineering has gained importance in the past decade. Increases in crop production have not been matched by technical improvements in post-production practices. Double and triple cropping, and the development of higher-yielding hybrids have led to significant production gains but the lack of post-harvest storage and processing facilities have resulted in greater post-production losses. *Volume IV of the CIGR Handbook of Agricultural Engineering* addresses this problem by presenting detailed treatises on the post-harvest technologies of agricultural products, ranging from the drying of grains to the value-added processing of olives. The Volume is a reference text in which essential agro-processing technology is assembled in an easily accessible form. It is intended to fill a gap in the presently available AE literature.

The *Handbook* will benefit both practicing engineers who are searching for answers to critical technical questions, and young students who are acquainting themselves with the principles of post-harvest technology. And, it will be useful to manufacturers, technicians, and (hopefully) farmers.

Volume IV is divided into five major sections. Part 1 covers the drying and storage of grains; Part 2 contains the storage of root crops; Part 3 is devoted to the storage and processing of fruits and vegetables; Part 4 includes the processing of grapes, olives and coffee; and, Part 5 concludes *Volume IV* with a description of the effluent treatment in several agro-processing industries. Each sub-section has a separate list of references. This plus an index should facilitate the search for specific information on Agro-processing topics.

The authors constitute a multi-national blend of academic, government and industrial experts. They were selected because of their long and broad experience in their fields of expertise. Space limitation forced each author to be selective in his/her choice of topics and depth of coverage; most emphasized the various *practical* engineering aspects of their agro-processing subject. Some unevenness among the chapters was unavoidable because of the different backgrounds of the authors, and the inequality of the technical development among the agro-processing domains. Some agro-processing topics are not covered in this Volume, e.g. wet-milling and dry-milling of maize, not because they are inconsequential but because of space limitation and handbook-availability of the subject elsewhere.

The Editors wish to thank Dr. A. A. Jongebreur (IMAG, Wageningen, the Netherlands) for serving as the critical reviewer of *Volume IV*. Thanks are also expressed to Donna Hull and her staff (ASAE, St. Joseph, MI, USA) for their support in the final editing of the manuscripts.

The Editor and Co-Editors of *Volume IV*

1 Grains and Grain Quality

F. W. Bakker-Arkema, Editor

Grains are among the major commodities for feeding mankind. The cleaning, drying, and storage of grains are postharvest operations required to maintain their product quality [1]. They are the major subjects discussed in this section.

The term *grains* is interpreted broadly and includes the cereal grains (maize, rice, wheat, sorghum, barley, oats, millet), the oil seeds (soybeans, sunflower seed, canola), and the pulses (edible beans). Although a grain species may require a particular postharvest operation, the fundamentals of the cleaning, drying, and storage of grains are sufficiently similar to warrant a general description of the various postharvest operations. This procedure is followed in this chapter.

1.1 Grain Quality

F. W. Bakker-Arkema

Grain quality is an ill defined term because its meaning is interpreted differently by various end-users. For the livestock producer, the nutritive value of grain is important. For the cereal manufacturer, some physical grain property such as the breakage susceptibility may be of significance. And to the seed producer, only the seed viability is of interest.

Regardless of the particular grain-quality criterion, the postharvest operations to which a grain sample is subjected determine its value.

1.1.1 Quality Factors

The property of a lot of grain that determines its market value may be a *physical* property, such as the kernel damage or the bulk density, or a *nutritive* value such as the crude protein or aflatoxin content. The next subsections cover the main physical and nutritive values of maize, rice, and wheat, principally.

Physical Properties

Moisture Content

The moisture content of grain can be expressed as a percentage on a wet basis (w.b.) (M_{wb}) or a dry basis (d.b.) (M_{db}):

$$M_{wb} = \frac{W_w}{W_t}(100)$$

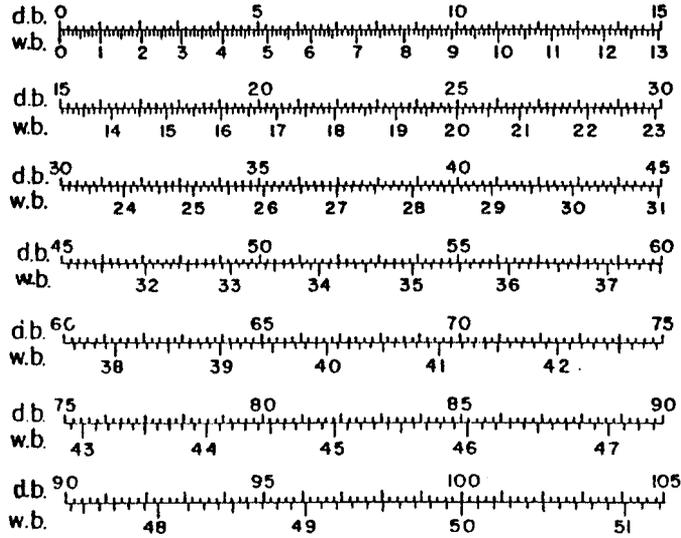


Figure 1.1. Scale for moisture-content basis conversion.

$$M_{db} = \frac{W_w}{W_{dm}}(100),$$

where W_w is the weight of water in a sample, W_{dm} is the weight of dry matter, and W_t is the total weight.

The relationship between M_{wb} and M_{db} is (see Fig. 1.1):

$$M_{wb} = \frac{M_{db}}{100 + M_{db}}(100)$$

$$M_{db} = \frac{M_{wb}}{100 - M_{wb}}(100).$$

M_{wb} is usually used in commerce, M_{db} in engineering calculations.

The methods of determining the moisture content of grains are listed in Fig. 1.2. Capacitance-type moisture meters are accurate over the range of moisture 12% to 30% (w.b.), if properly calibrated, and are popular for use in commerce.

Bulk Density

The *bulk density* of a lot of grain is defined as the weight per unit volume of grain kernels. It is expressed in grams per cubic centimeter or kilograms per cubic meter. In the United States the term *test weight* is used and is defined as the weight of 0.0352 m³ (i.e., 1 bushel) of grain.

The bulk density is determined by allowing grain to flow freely from a funnel into a so-called Winshester kettle and weighing the contents.

As grain is dried, the bulk density increases due to the shrinkage of the individual grain kernels. For maize and wheat the following empirical relationships have been established

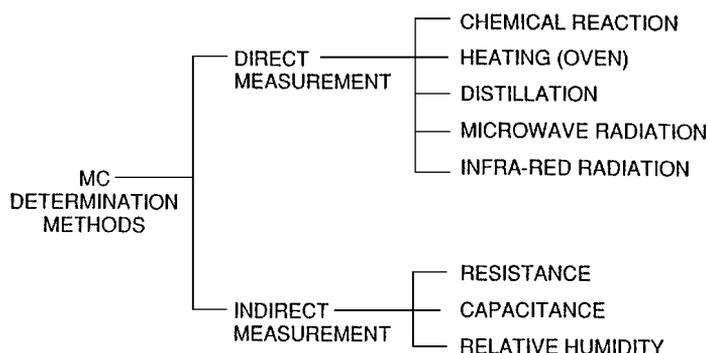


Figure 1.2. Classification of grain moisture-content (MC) determination methods.

between test weight and moisture content [2]:

$$\text{Maize: } TW_m = 0.7019 + 0.01676M_{wb} - 0.0011598M_{wb}^2 + 0.00001824M_{wb}^3$$

$$\text{Wheat: } TW_w = 0.7744 - 0.00703M_{wb} + 0.001851M_{wb}^2 - 0.000014896M_{wb}^3 \\ + 0.000003116M_{wb}^4,$$

where M_{wb} is the moisture content and TW is the test weight (g/cm^3).

Foreign or Fine Material

The foreign and fine material in a grain sample is defined as the particles passing through a screen of specified design, plus the large pieces of extraneous matter. For maize, a 4.76-mm round-hole sieve is used in the United States, for wheat a 1.98-mm round-hole sieve, and for soybeans a 3.18-mm round-hole sieve.

The foreign and fine material in a grain sample usually is measured in a dockage tester, which basically is a mechanical sieve shaker. The foreign and fine material content is expressed in terms of the percentage in weight of the original sample.

Kernel Damage

Damaged grain kernels include broken kernels, heat-damaged kernels, discolored kernels, or shrunken kernels. In grading a grain sample in the United States, the grader distinguishes between heat damage from high-temperature drying and heat damage resulting from mold activity. This latter type of kernel damage is counted under the category of total damage and not of heat damage.

Under the U.S. grain standards, the total damage category includes also the sprouted, germ-damaged, weather-damaged, molded, broken, and insect-damaged kernels.

The kernel-damage level of a grain sample is expressed as the percentage in weight of the original sample.

In some countries a special category of broken kernels is included separately in the grain standard. Usually the percentage of broken kernels is contained under total damage or defective kernels.

Stress Cracks

Stress cracks are small fissures in the internal endosperm of maize and rice kernels and are caused by large moisture-content gradients (and the resulting compressive and tensile stresses) within the kernels due to rapid moisture desorption or adsorption. Stress cracking often does not occur until 24 hours after drying or moisture adsorption.

Excessive stress cracking results in a high percentage of maize kernels breaking during handling operations, and in a low value of the head yield of rice after milling. The percentage of stress-cracked kernels in lots of maize and rice is determined by candling of 100 kernels over a 100- to 150-W light source.

Breakage Susceptibility

The breakage susceptibility of a grain sample is an indicator of the likelihood of the kernels to break up during handling and transport. It can be considered as an indirect measure of the number and size of the stress cracks in the kernels of a grain sample. The concept of breakage susceptibility is used for evaluating the quality of maize, mainly by researchers in comparing different maize hybrids and various maize-drying systems.

The breakage susceptibility is measured with a Stein Breakage Tester (model CK-2M), the only commercially available unit (Stein Laboratories, Kansas City, Kansas, U.S.A.). A 100-g maize sample at 14% to 15% moisture content (w.b.) is put in a steel cylindrical cup in which an impeller is rotated at 1790 rpm for 2 minutes. Subsequently, the sample is screened on a 4.76-mm round-hole sieve. The weight loss of the original sample is expressed as a percentage and constitutes its breakage susceptibility.

Viability

The viability is defined as the ability of the seed to develop into a young plant under favorable growing conditions and is expressed as a percentage. The viability of a sample of grain is of interest principally if the grain is to be used for seed. (Viability is too stringent a measure for the quality of grain.) Seed grain usually is marketed with a minimum viability (e.g., seed maize in the United States has a viability of at least 95%).

The viability of a grain sample can be determined by a wet-paper test (i.e., placing 100 seeds wrapped in wet paper for 7–10 days at 15–30°C, and counting the kernels that germinate properly), or by a tetrazoleum test (i.e., measuring the activity of the enzyme dehydrogenase by the intensity of germ coloration as an index of seed viability) [3].

Nutritive Properties

Nutritive Attributes

The nutritive value of grains is of importance to humans and animals alike. The significant nutritive properties of grains are as follows [4]:

- Ash
- Crude fiber

- Crude protein
- Ether extract
- Feed analysis
- Gross energy
- Metabolizable energy
- Nitrogen-free extract
- Total digestible nutrients

Deleterious Substances

Grains are injurious as a food and feed if degraded by certain toxic fungal metabolites and chemical residues.

Mycotoxins. Grains stored at excessively high moisture content and temperature will mold. Over 100 mold species have been isolated from grains, and some produce toxins under certain circumstances. Of particular concern are *Aspergillus flavus* and *Aspergillus parasiticus*, both able to yield aflatoxin, a substance of extreme toxicity. Other mycotoxins occurring in some grains, often due to improper storage, are fumonisin, ochratoxin, vomitoxin, and zearalenone. The reader is referred to Ref. [5] for recent information on these grain toxins.

Aflatoxins are the major toxins occurring in grains. They develop principally from mold growth in the field but can further evolve in storage. More than 10 forms of aflatoxins have been identified, with aflatoxin B1 the most toxic. Aflatoxins have been found in all grains but are of particular concern in maize grown and stored under semitropical conditions (i.e., 27–30°C and 85%–95% relative humidity).

Many countries have set limits on the maximum toxin level in commercially traded grains. For maize in the United States the current (1998) limits for aflatoxin are [6]: 20 parts per billion for humans, immature cattle, and dairy cattle; 100 parts per billion for breeding beef cattle, poultry and swine; 200 parts per billion for finishing swine; and 300 parts per billion for finishing beef cattle. The reader should consult local health authorities on the limits for the various toxins found in grains in their country. The tolerance limits in France for the major toxins in cereal grain for food and feed processing are given in Table 1.1. A zero tolerance for grain toxins for export grain has been established in some countries [6].

A variety of laboratory methods is employed to determine the presence of toxins in grains, varying from the relatively simple qualitative tests (e.g., the backlight test) to more complex quantitative test methods (e.g., the thin-layer chromatography test). The reader is encouraged to contact a local grain-testing agency if it is suspected that a lot of grain contains dangerous toxins.

Chemical Residues. In some countries, there is a market demand for crops grown without application of any chemicals, in particular fertilizers, herbicides, and insecticides. Customers of such “organic” products demand production practices during the production year, and for the 2 preceding years, that do not include the use of any chemicals; and postharvest production practices that do not encompass the employment of insecticides.

Table 1.1. Tolerance limits for the major mycotoxins in cereal grain for food and feed processing in France in 1996

Mycotoxin	Limit
Aflatoxin B1	5 ppb in cereal grain 1 ppb in grain for food 0.5 ppb in edible oil
Zearalenone	20 ppb in corn for food 1 ppb in corn oil 300 ppb in pig feed 500 ppb for other animal feed
Ochratoxin A	30 ppb in cereal grain
Fumonisin	5 ppb in food and feed for all species

Source: [7].

Verifying the nonuse of chemicals during the production and postharvest operations of a food or feed product requires testing at a specially equipped laboratory and thus is an expensive procedure.

Milling and Processing Properties

Grains are used as feed for animals, as food for humans, and as feedstock for industrial processes. As a feed, the nutritive properties have to be healthy. As a food or feedstock, the milling and processing qualities of grains have to be acceptable. The desired attributes differ greatly for the various grains, as is shown in Table 1.2. Note that these attributes are *in addition to* the factors contained in the grade standard (see Section 1.1.2) for each grain.

1.1.2 Grade Standards

Grade standards are used in the trade of grain; they facilitate the marketing of grains. Unfortunately, the grade standards of the various grain species are not universal but

Table 1.2. Grain-quality attributes of importance for the milling, processing, or human consumption of different grains

Maize	Rice	Soybeans	Wheat
Hardness	Milling quality	Splits	Hardness
Kernel weight	Cooking quality	Kernel weight	Kernel weight
Fat acidity	Kernel color	Protein content	Gluten content
Soluble protein	Eating quality	Oil content	Fat acidity
Turbidity		Free fatty acids	Flour yield
Sedimentation		Iodine number	Semolina yield
Amylose		Phosphatides	Ash content
		Oxidation value	Dough quality

Sources: [1, 8].

Table 1.3. U.S. grade requirements for yellow corn (maize)

	Minimum Test Weight per Bushel (lb)	Maximum Limits (%)		
		Damaged Kernels		Broken Corn and Foreign Material
		Heat-Damaged Kernels	Total	
U.S. no. 1	56.0	0.1	3.0	2.0
U.S. no. 2	54.0	0.2	5.0	3.0
U.S. no. 3	52.0	0.5	7.0	4.0
U.S. no. 4	49.0	1.0	10.0	5.0
U.S. no. 5	46.0	3.0	15.0	7.0
U.S. sample grade ^a				

Source: [1].

^a U.S. sample-grade is corn that does not meet the requirements for U.S. grade nos. 1, 2, 3, 4, or 5; contains eight or more stones that have an aggregate weight in excess of 0.20% of the sample weight, or two or more pieces of glass; has a musty, sour, or commercially objectionable foreign odor; or is heating or otherwise of distinctly low quality.

Table 1.4. Maximum allowable percentages of grade factors for dent maize in Argentina

	No. 1	No. 2	No. 3	No. 4
Damaged kernels	3.0	5.0	8.0	12.0
Broken kernels	2.0	3.0	5.0	5.0
Foreign material	1.0	1.5	2.0	2.0

Source: [9].

Table 1.5. Maximum allowable percentages of grade factors for yellow maize in South Africa

	No. 1	No. 2	No. 3
Defective maize kernels	3.0	5.0	8.0
Other-colored maize kernels	2.0	3.0	5.0
Foreign matter	1.0	1.5	2.0
Sum of the above three defects	9.0	20.0	30.0
Pink corn	12.0	12.0	12.0

Source: [9].

may vary significantly between countries. This is illustrated for maize in Tables 1.3 through 1.5 for the United States, Argentina, and South Africa, respectively. Only the U.S. standard contains a factor for test weight; only South Africa includes a category of pink maize.

It is noteworthy that the grade standard for maize does not contain a factor for moisture content in either of the three countries. However, in the trade the maximum average moisture content of a lot usually is specified.

Table 1.6. U.S. grade requirements for rough rice

Grade	Maximum Limits									
	Seeds and Heat-Damaged Kernels					Chalky Kernels				
	Total, Singly or Combined (no. per 500 g)	Heat-damaged Kernels and Objectionable Seeds (Singly or Combined) (no. per 500 g)	Heat-damaged Kernels (no. per 500 g)	Red Rice and Damaged Kernels, Singly or Combined (%)	In Long-grain Rice (%)	In Medium-grain or Short-grain Rice (%)	Other Types (%)	Color Requirements (Minimum)		
U.S. no. 1	4	3	1	0.5	1.0	2.0	1.0	1.0	Shall be white or creamy	
U.S. no. 2	7	5	2	1.5	2.0	4.0	2.0	2.0	May be slightly gray	
U.S. no. 3	10	8	5	2.5	4.0	6.0	3.0	3.0	May be light gray	
U.S. no. 4	27	22	15	4.0	6.0	8.0	5.0	5.0	May be gray or slightly rosy	
U.S. no. 5	37	32	25	6.0	10.0	10.0	10.0	10.0	May be dark gray or rosy	
U.S. no. 6	75	75	75	15.0	15.0	15.0	10.0	10.0	May be dark gray or rosy	
U.S. sample grade ^a										

Source: [1].

^a U.S. sample grade shall be rough rice that does not meet the requirements for any of the grades from U.S. no. 1 through no. 6, inclusive; contains more than 14.0% moisture (w.b.); is musty, sour, or heating; has any commercially objectionable foreign odor; or is otherwise of distinctly low quality.

It should be noted that the physical grain-quality factors of stress cracks and breakage susceptibility are not part of the grade standards for maize in any of the three countries, notwithstanding their importance to grain marketers.

The U.S. grain-grading standards are offered here as an example of the present (1998) set of standards employed for the marketing of four major grains (i.e., maize, rough rice, soybeans, wheat) in one country. The reader should check with the official marketing agency in a particular country for its latest grain-grading standards. Note that in the U.S. standards the test weight is quoted on a bushel (0.03524-m^3) basis in terms of pounds (0.4536 kg).

The factors included in the U.S. grades and grade requirements for maize (corn) are (see Table 1.3) test weight, heat-damaged kernels, total damaged kernels, and broken kernels and foreign material. There are five grades for maize, plus a sample grade.

The factors included in the U.S. grades and grade requirements for rough rice are (see Table 1.6) heat-damaged kernels, heat-damaged and objectionable kernels, the sum of these first two, red rice kernels, chalky kernels, and other seeds. The requirement for the maximum limit of chalky kernels differs for long-grain and medium- or short-grain rice. There are six grades for rough rice, plus a sample grade.

The factors included in the U.S. grades and grade requirements for soybeans are (see Table 1.7) test weight, heat-damaged kernels, total damaged kernels, foreign material, splits, and off-color kernels. There are four grades for soybeans, plus a sample grade.

The factors included in the U.S. grades and grade requirements for all classes of wheat are (see Table 1.8) test weight, heat-damaged kernels, total damaged kernels, foreign material, shrunken and broken kernels, defected kernels, and wheat of other classes. Only the test-weight requirement varies among the various classes of wheat. There are five grades for wheats, plus a sample grade.

For the U.S. grades and grade requirements for barley, oats, sorghum and sunflower seeds, the reader is referred to Ref. [10].

Table 1.7. U.S. grade requirements for soybeans

	Minimum Test Weight per Bushel (lb)	Maximum Limits (%)				Soybeans of Other Colors
		Damaged Kernels		Foreign Material	Splits	
		Heat-damaged	Total			
U.S. no. 1	56.0	0.2	2.0	1.0	10.0	1.0
U.S. no. 2	54.0	0.5	3.0	2.0	20.0	2.0
U.S. no. 3	52.0	1.0	5.0	3.0	30.0	5.0
U.S. no. 4	49.0	3.0	8.0	5.0	40.0	10.0
U.S. sample grade ^a						

Source: [1].

^a U.S. sample grade is soybeans that do not meet the requirements for U.S. grade nos. 1, 2, 3, or 4; contain eight or more stones that have an aggregate weight in excess of 0.2% of the sample weight, or two or more pieces of glass; have a musty, sour, or commercially objectionable foreign odor (except garlic odor); or are heating or otherwise of distinctly low quality.

Table 1.8. U.S. grade requirements for all classes of wheat except mixed wheat

	Minimum Test Weight per Bushel (lb)		Maximum Limits (%)									
	Hard Red Spring Wheat or White Club Wheat	All Other Classes and Subclasses	Damaged Kernels			Foreign Material	Shrunken and Broken Kernels	Defects	Wheat of Other Classes			
			Heat-Damaged Kernels	Total	Total				Contrasting Classes	Total		
U.S. no. 1	58.0	60.0	0.2	2.0	0.5	3.0	3.0	1.0	3.0			
U.S. no. 2	57.0	58.0	0.2	4.0	1.0	5.0	5.0	2.0	5.0			
U.S. no. 3	55.0	56.0	0.5	7.0	2.0	8.0	8.0	3.0	10.0			
U.S. no. 4	53.0	54.0	1.0	10.0	3.0	12.0	12.0	10.0	10.0			
U.S. no. 5	50.0	51.0	3.0	15.0	5.0	20.0	20.0	10.0	10.0			
U.S. sample grade ^a												

Source: [1].

^a U.S. sample grade is wheat that does not meet the requirements for U.S. grade nos. 1, 2, 3, 4, or 5; contains 32 or more insect-damaged kernels per 100 g of wheat; contains eight or more stones or any number of stones that have an aggregate weight in excess of 0.2% of the sample weight, or two or more pieces of glass; has a musty, sour, or commercially objectionable foreign odor (except smut or garlic odor); is heating or otherwise of distinctly low quality.

References

1. Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1992. *Drying and Storage of Grains and Oilseeds*. New York: Van Nostrand Reinhold.
2. Nelson, S. O. 1980. Moisture-dependent kernel and bulk density for wheat and corn. *Trans. ASAE* 23:139–143.
3. Copeland, L. O., and M. B. McDonald. 1985. *Principles of Seed Science and Technology*, 2nd ed. Minneapolis, MN: Burgess.
4. Ensminger, S. 1991. *Feeds and Nutrition*. San Francisco: Ensminger.
5. Pitt, J. I. 1996. What are mycotoxins? *Australian Mycotoxin Newsletter* 7:1–2.
6. U. S. Feed and Grain Council. 1997. Mycotoxins in feed. *World Grain* 15:30–31.
7. Cahagnier, B., and M. Fremy. 1996. Mycotoxins. *Proc. J. Tech. GLCG* 5:68–70.
8. Godon, B., and C. Willm, eds. 1994. *Primary Cereal Processing*. New York: VCH Publishers.
9. Paulsen, M. R., and L. D. Hill. 1985. Corn quality factor affecting dry milling performance. *J. Agric. Eng. Res.* 31:225–263.
10. Hill, L. D. 1982. Grain standards for corn in exporting countries. In *Evaluation of Issues in Grain Grades and Optimum Moistures*. Urbana: University of Illinois.
11. USDA, 1988. *Grain Grading Procedures*. Washington, DC: Federal Grain Inspection Service.

1.2 Grain Handling

J. S. Labiak and R. E. Hines

Grain-handling equipment is available for any situation under which grain must be transported from one location to another. The four types most commonly used for commercial and farm applications are belt, screw, bucket, and pneumatic conveyors. Grain-flow rate, distance, incline, available space, environment, and economics influence conveyor design and operating parameters.

The objective of this section is to provide an overview of conveyor designs and operating characteristics. Power requirement and capacity calculations are different for each conveyor type and often are based on empirical data. It is suggested to use model-specific, manufacturer-provided information for these calculations, or the procedures referenced in this section if manufacturer information is unavailable. Design of conveyors is covered in detail in the agricultural-engineering literature [1, 2] and in the chemical-engineering literature [3, 4].

The physical characteristics of the material to be handled must be known before the appropriate conveying system can be selected. In particular, the following properties are relevant for agricultural products: moisture content, average weight per unit volume, angle of repose, and particle size. The physical characteristics of grains and related agricultural products are shown in Table 1.9.

In order to use general conveyor-design procedures, the material to be handled first should be classified. The U.S. Conveyor Equipment Manufacturers Association distinguishes among four classes of solids handled by materials-handling systems [8]. Grains

Table 1.9. Characteristics of agricultural products

	Bulk Density (kg/m ³)	Moisture Content Range for Handling (% w.b.)	Angle of Repose (degrees)	Source
Barley	618	7.9–23.1	29.0–33.8	[5, 6]
Maize	721	7.5–23.1	34.0–43.5	[6, 7]
Oats	412	10.6–17.3	11.3–33.0	[7]
Sorghum	721	6.8–22.1	11.3–23.7	[6]
Soybeans	722	7.1–12.2	11.9–28.8	[7]
Wheat	772	7.3–19.3	29.6–41.0	[6]

are relatively lightweight, free-flowing, noncorrosive, and nonabrasive and are defined as class I products. Class II solids are moderately free-flowing and are mixed with small lumps and fines; alfalfa meal and maize grits fall into this class. Class III materials are similar in size and flowability to class II solids but are more abrasive and include cement. Class IV products are abrasive and flow poorly; the class includes coal and dry sand.

1.2.1 Belt Conveyors

Design

The simplest belt conveyor consists of an endless flat or troughed belt wrapped around two rotating drums. Bulk materials are transported horizontally on the surface of the belt or can be inclined or declined within product-specific limits. Support for the belt is provided by a head (drive) and a tail pulley, and by a series of idler rollers. The belt-conveyor structure supports the entire system and maintains belt alignment. A typical belt-conveyor design is shown in Fig. 1.3, the cross-section is illustrated in Fig. 1.4

Types Used for Grain

Belt conveyors can be designed to satisfy almost any transport situation requirement. Modifications of the basic troughed design are available for different applications, depending on the required dust control, available space, transport length and height, conveying rate, number of discharge points, and product characteristics [1, 9].

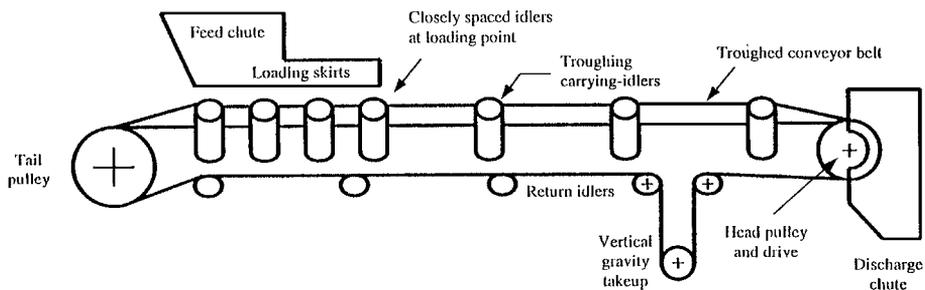


Figure 1.3. Troughed-belt conveyor [8].

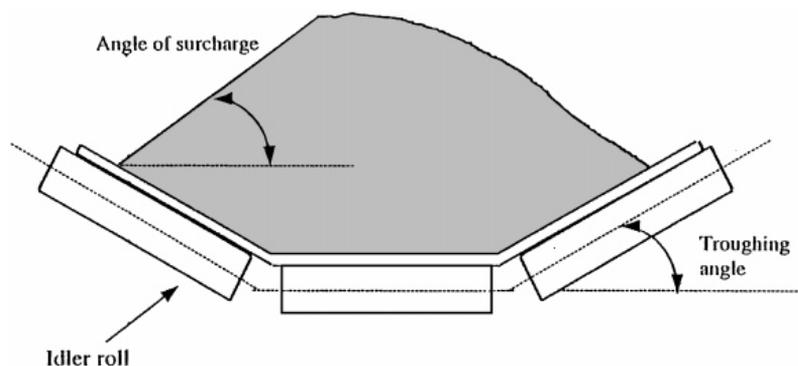


Figure 1.4. Cross-section of troughed-belt conveyor [8].

Appropriateness for Grain

Belt conveyors are used in commercial operations but generally not on farms, unless a specialty crop warrants the extra costs. Belt conveyors cause less product damage than other types of conveyors. Elevation is limited and depends on the product being conveyed but is generally less than 15 degrees. Long-distance conveying is easily accomplished.

Operating Characteristics

The angle between the idler rolls and the horizontal is called the *troughing angle*. The range for conveying grains is 20 to 45 degrees. The capacity and power requirement depend on the grain mass and cross-sectional area of the belt, and on the conveyor length, incline, and belt speed [10, 11]. In calculating the cross-sectional area of grain on the belt, the triangular area defined by the grain angle of repose is neglected. This prevents spillage as grain is conveyed. The maximum belt speed to prevent airborne particles is 3.5 m/s for maize-kernel shaped grains, 2.8 m/s for soybeans, and 2.5 m/s for light grain derivatives [1]. Dust, noise, and spillage are minimized by limiting the belt speed to 2.5 m/s. Typical operating parameters for troughed belt conveyors transporting shelled maize are shown in Table 1.10.

Table 1.10. Typical operating characteristics of troughed-belt conveyors for maize

Belt Width (cm)	Belt Speed (m/h)	Power Requirement (kW/m)	Capacity (kg/h)
46	210	0.74	3700
60	210	0.97	6300
76	210	1.2	10100
91	210	1.5	14500

Adapted from [3].

Note: Data for horizontal conveying, roller angle = 35 degrees, center belt width = one third of the total belt width, moisture content = 16% w.b.

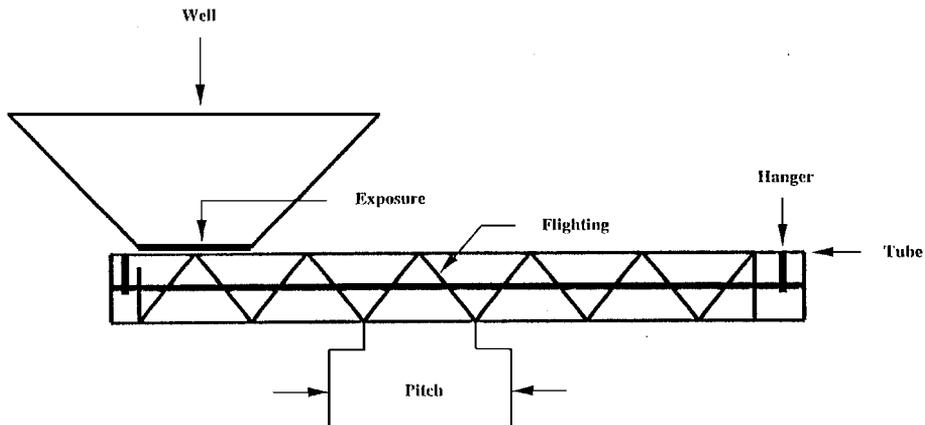


Figure 1.5. Screw conveyor [12].

1.2.2 Screw Conveyors

Design

A screw conveyor, or auger, consists of a circular or U-shaped tube in which a helix rotates, as shown in Fig. 1.5. Grain is pushed along the bottom of the tube by the helix; thus the tube does not fill completely. Important parameters of the auger—the diameter, pitch, and exposed intake length—are indicated on the figure.

Types Used for Grain

Both U-shaped and circular screw conveyors are used for grains. If the angle of elevation increases beyond 15 degrees, augers with circular cross-section should be used.

Appropriateness for Grain

Screw conveyors are used extensively on both farms and grain depots. Advantages of this type of conveyor include portability, low cost, low maintenance, and low dust emission. They are not practical for high capacity or long transport distances due to high power requirements. Typical models available commercially have diameters from 10.2 to 30.5 cm, with rated capacities from about 10 to 300 m³/h, and maximum length of 25 m [13].

Typical uses for screw conveyors include conveying grain from storage bins and transport vehicles, mixing grain in storage, and moving grain in a bin to a central unloading point. Augers are also a good choice when the flowrate is monitored.

Operating Characteristics

Auger capacity and power requirements depend on the diameter, pitch, speed (rpm), exposed intake length, incline, and grain properties. Empirical methods for estimating capacity and power normally are used [12–14]. Performance data usually are guaranteed by the manufacturer. Typical screw-conveyor capacity and power-requirement data are given in Table 1.11.

Table 1.11. Approximate characteristics of standard-pitch augers

Auger Diameter (cm)	Auger Speed ^a (rpm)	0° Incline Angle			25° Incline Angle			35° Incline Angle			45° Incline Angle		
		Capacity (m ³ /h)	Power Requirement (kW/m)	Power Requirement (kW/m)	Capacity (m ³ /h)	Power Requirement (kW/m)	Power Requirement (kW/m)	Capacity (m ³ /h)	Power Requirement (kW/m)	Power Requirement (kW/m)	Capacity (m ³ /h)	Power Requirement (kW/m)	Power Requirement (kW/m)
10.2	900 ^b	20	0.15	0.22	18	0.22	0.22	17	0.22	0.22	16	0.25	
15.2	600	53	0.25	0.37	48	0.37	0.39	46	0.39	0.39	42	0.39	
20.3	450	78	0.34	0.54	70	0.54	0.54	67	0.54	0.54	62	0.56	
25.4	360	116	0.49	0.76	105	0.76	0.78	100	0.78	0.78	92	0.78	
30.5	300	150	0.61	0.96	143	0.96	0.98	140	0.98	0.98	130	0.98	
35.6	260	220	0.83	1.3	198	1.3	1.3	190	1.3	1.3	170	1.3	
40.6	225	280	1.1	1.7	255	1.7	1.7	240	1.7	1.7	230	1.7	

Source: [14].

Note: For dry (14% maximum moisture content) maize. Values for 10.2-cm and 15.2-cm augers are based on experimental data. Values for 20.3-cm and 25.4-cm augers are based on limited data. Values for 30.5–40.6-cm augers were extrapolated. Actual auger performance may vary; use manufacturer's data for designing auger systems. Multiply dry maize values by 0.6 for wet maize capacity. Use table values for wheat, sorghum, oats, barley, and rye, because actual values are only slightly less. For soybeans, multiply capacity by 0.75 and power by 1.10.

^a Auger speeds for 232 m/min flighting velocity along auger length (theoretical grain velocity) for all diameters.

^b 10.2-cm auger at 900-rpm vibrates excessively; 900-rpm values are for converting with capacity and power-conversion tables.

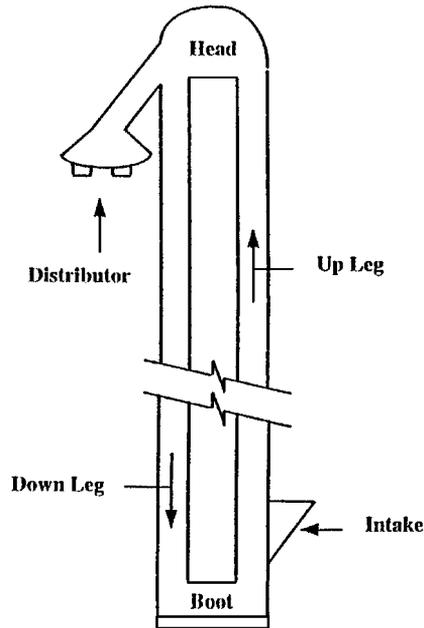


Figure 1.6. Bucket Elevator [12, 14].

Theoretical studies of screw conveyor performance with grains are rare; the best mathematical model appears to be Ref. [15].

Augers are the conveyor type most likely to cause significant grain damage. To minimize the damage, the speed should be kept below the recommended limit, the auger should be operated at full capacity, and the auger should have a clearance between the flighting and casing of either greater or smaller than the diameter of the grain kernels.

1.2.3 Bucket Elevators

Design

A bucket elevator is essentially a modified belt conveyor. Buckets are attached to an endless belt and convey the product vertically (Fig. 1.6).

The components include the head section at the grain outlet (top), the boot section at the grain inlet (bottom), the supporting frame, a device to maintain correct belt tension, and the grain distributor. The enclosed section of the belt between the head and boot is called the leg; the up-leg and down-leg sections often are physically separated within individual enclosures.

Types Used for Grain

Two bucket-elevator designs exist: the centrifugal-discharge and the continuous-bucket types. Grain is removed at the head section by centrifugal action in the centrifugal-discharge design, and by gravity in the continuous-bucket design. Centrifugal-discharge bucket elevators are used almost exclusively in grain-handling operations. Bucket

elevators sometimes employ chains instead of belts as the conveying mechanism, but the chain design is not used for grains because a chain cannot operate at the speed required for centrifugal discharge. The elevator intake may be on the up-leg or down-leg side, but the up-leg side is recommended for high-capacity grain transport.

Appropriateness for Grain

Bucket elevators are an effective grain conveying system and typically are located at the central point of a grain-handling system. Once grain is emptied from transport vehicles, it usually is elevated by a bucket elevator and distributed to a system component (e.g., storage or a drying system). Animal feed, meal, and wet and dry grain can be conveyed with bucket elevators at lower power requirements than with other conveying systems. Grain damage is less than damage caused by augers; it decreases at slower belt speeds and full-bucket operation [16]. The initial cost of bucket elevators is greater than that of other conveying systems, but increased efficiency and convenience often justify the cost.

Operating Characteristics

The capacity of bucket elevators is a function of the product density, belt speed, bucket size, and bucket spacing. The power requirement depends on the capacity and product-elevating height, as shown in Table 1.12.

When sizing a bucket elevator, the size of the dump pit and the desired grain-unloading capacity should be considered [12]. An important operating parameter of centrifugal-discharge bucket elevators is the belt speed. The discharge features are determined by the belt speed, product characteristics, and the elevator-component size [10]. The belt speed should be above 80 m/h to achieve the desired discharge characteristics.

1.2.4 Pneumatic Conveyors

Design

A pneumatic conveying system introduces grain into a moving airstream, which carries the grain to a single location or multiple locations. The main components include the blower, the transport tubing, and the device to introduce the grain into the tubing at

Table 1.12. Typical bucket elevator data for maize

Capacity (m ³ /h)	Belt Speed (m/min)	Bucket Size (cm)	Bucket Spacing (cm)	Power (kW/m)
35	101	22.9 × 12.7	30.5	0.098
53	115	22.9 × 12.7	22.9	0.147
70	101	22.9 × 12.7	15.2	0.196
88	129	22.9 × 12.7	15.2	0.245
106	151	22.9 × 12.7	15.2	0.294
141	151	22.9 × 15.2	16.5	0.392

Source: [17].

Note: Data for 25.4-cm belt width; power requirements based on overall efficiency of 80% of shaft power.

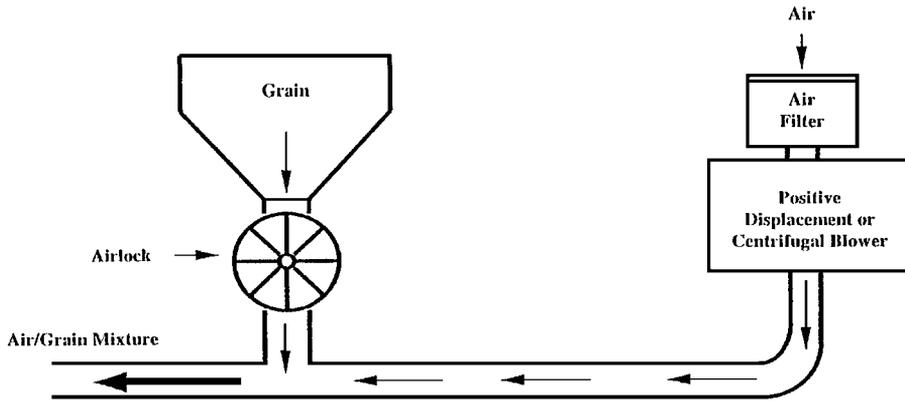


Figure 1.7. Positive-pressure pneumatic conveying system (adapted from [12]).

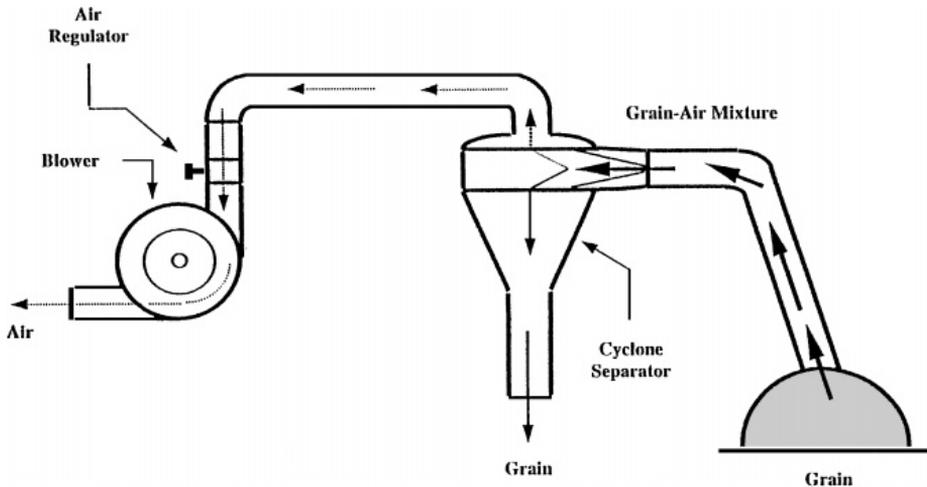


Figure 1.8. Negative-pressure pneumatic conveying system [12].

the grain source and out of the tubing at the grain destination. Two pneumatic conveyor types, positive-pressure and negative-pressure, are shown in Figs. 1.7 and 1.8.

Types Used for Grain

The main pneumatic conveyor designs are the positive-pressure design, the negative-pressure design, and the positive/negative combination design. Negative-pressure systems are used for conveying materials from multiple sources to a single destination. Positive-pressure systems are employed for conveying materials from a single source to multiple destinations. Pneumatic conveying systems employing both positive- and negative-pressure sections are used for conveying from multiple sources by vacuum to multiple destinations by positive pressure.

Table 1.13. Typical pneumatic-conveyor characteristics

Pipe Diameter (cm)	Capacity (m ³ /h)	Power (kW)
7.6	14.1	7.6
10.2	24.7	11.5
12.7	42.3	15.3–22.9
15.2	70.5	30.6–38.2

Source: [14].

A low-capacity on-farm design typically is powered by an electric motor. High-capacity designs are powered by internal combustion engines, such as the power takeoff on a tractor.

Appropriateness for Grain

The primary advantage of a pneumatic conveying system is the flexibility of the conveying path. Storage bins not reachable by other conveyor types can be readily loaded or unloaded with a pneumatic conveyor. However, the power requirements of pneumatic conveyors are high relative to other conveyor types.

Low-capacity requirements with odd conveying paths are appropriate for pneumatic systems. Automated control systems can be implemented easily on pneumatic conveyors.

Operating Characteristics

The capacity of pneumatic conveyors depends on the grain type, tube length, number of turns, and elevation [18]. The power requirements are approximately 0.6 to 0.7 kw·h/m³ material, compared with 0.1 to 0.2 kw·h/m³ for bucket elevators [14]. Typical power requirements and capacity data are shown in Table 1.13.

A sharp change in tube direction should be avoided because it increases grain damage and prematurely wears out the tube. Grain damage is minimized by keeping the air velocity below 25 m/s and the air-to-grain volume ratio at manufacturer's specifications. Fines in the grain cause plugging of the filter or choking of the blower in negative-pressure systems, especially with sunflower seeds [14]. The blower in a pneumatic conveyor must be started before grain enters the system and turned off after all lines are empty. Removal of "dead" material from the lines usually requires disassembly of the tube section.

Detailed design and operating information for pneumatic conveyors can be found in Ref. [18].

References

1. Boumans, G. 1985. *Grain Handling and Storage*. New York: Elsevier.
2. Norder, R., and S. Weiss. 1984. Bucket elevator design for farm grains. Paper No. 84-3512. St. Joseph, MI: ASAE.
3. Buffington, M. A. 1969. Mechanical conveyors and elevators. *Chemical Engineering* 76:41–43.
4. McNaughton, K. 1981. *Solids Handling*. New York: McGraw-Hill.

5. USDA. 1985. Table of Weights and Measures in Agricultural Statistics. Washington, DC.
6. Lorenzen, C. 1959. Moisture effect on granular friction of small grain. Paper No. 59-416. St. Joseph, MI: ASAE.
7. Brubaker, J. E., and J. Pos. 1965. Determining the static coefficient of friction of grains on structural surfaces. *Trans. ASAE* 8:53–55.
8. Colijn, H. 1978. Mechanical conveyors and elevators. Hightstown, NJ: *Chemical Engineering*.
9. Hartsuiker, H. 1984. Horizontal conveying options and hydraulic machinery application. In *Retrofitting and Constructing Grain Elevators for Increased Productivity and Safety*, ed. R. C. Gordon. Washington, DC: National Grain and Feed Association.
10. Henderson, S. M., and M. E. Perry. 1976. *Agricultural Process Engineering*. Westport, CT: AVI.
11. Brook, B. 1971. *Mechanics of Bulk Handling*. Bath, UK: Butterworth & Co.
12. Loewer, O. J., T. C. Bridges, and R. A. Bucklin. 1994. *On-farm Drying and Storage Systems*. St. Joseph, MI: ASAE.
13. Pierce, R. O., and B. A. McKenzie. 1984. Auger performance data summary for grain. Paper No. 84-3514. St. Joseph, MI: ASAE.
14. Midwest Plan Service. 1987. *Grain Drying, Handling, and Storage Handbook (MWPS-13)*. Ames, IA: Midwest Plan Service.
15. Roberts, A. W., and A. H. Willis. 1962. Performance of grain augers. *Proc. Instn. Mech. Engrs* 176:165–194.
16. Hall, G. E. 1974. Damage during handling of shelled corn and soybeans. *Trans. ASAE* 17:335–338.
17. Brooker D. B., F. W. Bakker-Arkema, and C. W. Hall. 1992. *Drying and Storage of Grains and Oilseeds*. New York: Van Nostrand Reinhold.
18. Marcus, R. D., L. S. Leung, G. E. Klinzing, and F. Rizk. 1990. *Pneumatic Conveying of Solids*. New York: Chapman and Hall.

1.3 Grain Drying

Qiang Liu, C. W. Cao, and F. W. Bakker-Arkema

1.3.1 Fundamentals

Grain drying is a process of simultaneous heat and moisture transfer. To adequately understand the operation of drying, the reader has to be acquainted with the basics of psychrometrics, equilibrium moisture content, airflow, and drying rate. These are the topics briefly reviewed in this subsection.

Psychrometrics

Air is the medium in which grain is dried. The major physical properties of air that affect the drying rate of grains are the relative humidity or humidity ratio, the dry-bulb temperature, the specific volume, and the enthalpy.

The *relative humidity* (RH) of air is the ratio of the vapor pressure of the water molecules in the air to the saturated vapor pressure at the same temperature. The relative humidity usually is expressed as a percentage. A second term expressing the moisture content of the air is the *humidity ratio* (W), the mass of water vapor per unit mass of dry air (kg/kg).

The *dry-bulb temperature* (T) of air is the temperature measured with an ordinary thermometer. If the term *temperature* is used without a prefix, dry-bulb temperature is implied. Another temperature commonly used in grain drying is the wet-bulb temperature (it is measured by covering the bulb of a thermometer with a wet wick). Knowledge of the dry-bulb and wet-bulb temperatures allows rapid determination of the relative humidity of the air on a psychrometric chart (see Fig. 1.9). The temperatures of air are expressed in degrees Centigrade ($^{\circ}C$).

The *specific volume* (v) of moist air is the volume per unit mass of dry air and is expressed in cubic meters per kilogram of dry air. The power required by the fan on a drying system is affected by the specific volume of the drying air.

The *enthalpy* (h) of moist air is the energy content per unit mass of dry air above a certain reference temperature (usually $0^{\circ}C$). It is denoted in kilojoules per kilogram of dry air. Determination of the burner size in a dryer requires knowledge of the enthalpy values of the air before and after heating.

Equations and computer packages have been developed for the calculation of the psychrometric properties of air [1]. Before the evolution of computer technology, the so-called psychrometric charts for moist air were developed to facilitate the determination of the psychrometric properties. Figures 1.9 and 1.10 show psychrometric charts in the 1 to $50^{\circ}C$ and 10 to $120^{\circ}C$ temperature ranges, respectively.

The horizontal axis on the psychrometric chart represents the dry-bulb temperature; the humidity ratio serves as the vertical axis. The curved lines on the chart represent constant relative humidity values. Figure 1.11 illustrates how the various psychrometric values of moist air can be determined once two properties (e.g., dry-bulb temperature and RH) are known.

The process of grain drying is represented on a skeletal psychrometric chart in Fig. 1.12. As the air passes through the heater, its dry-bulb temperature and enthalpy increase. The relative humidity and humidity ratio of the air increase as it passes through the grain, while the dry-bulb temperature decreases and the enthalpy remains almost constant.

Equilibrium Moisture Content

The *equilibrium moisture content* (EMC) of a grain species is the moisture content to which the grain will dry after it has been exposed to the drying air for an infinite period of time. The EMC of a grain sample is a function of the air temperature and RH , and of the grain species and (to some degree) of the sample history. Table 1.14 gives the EMC values of some grains at $25^{\circ}C$.

Plotting the EMC values of a grain species at a specific temperature versus the RH of the surrounding air results in a sigmoid curve. This is illustrated for three grains in Fig. 1.13.

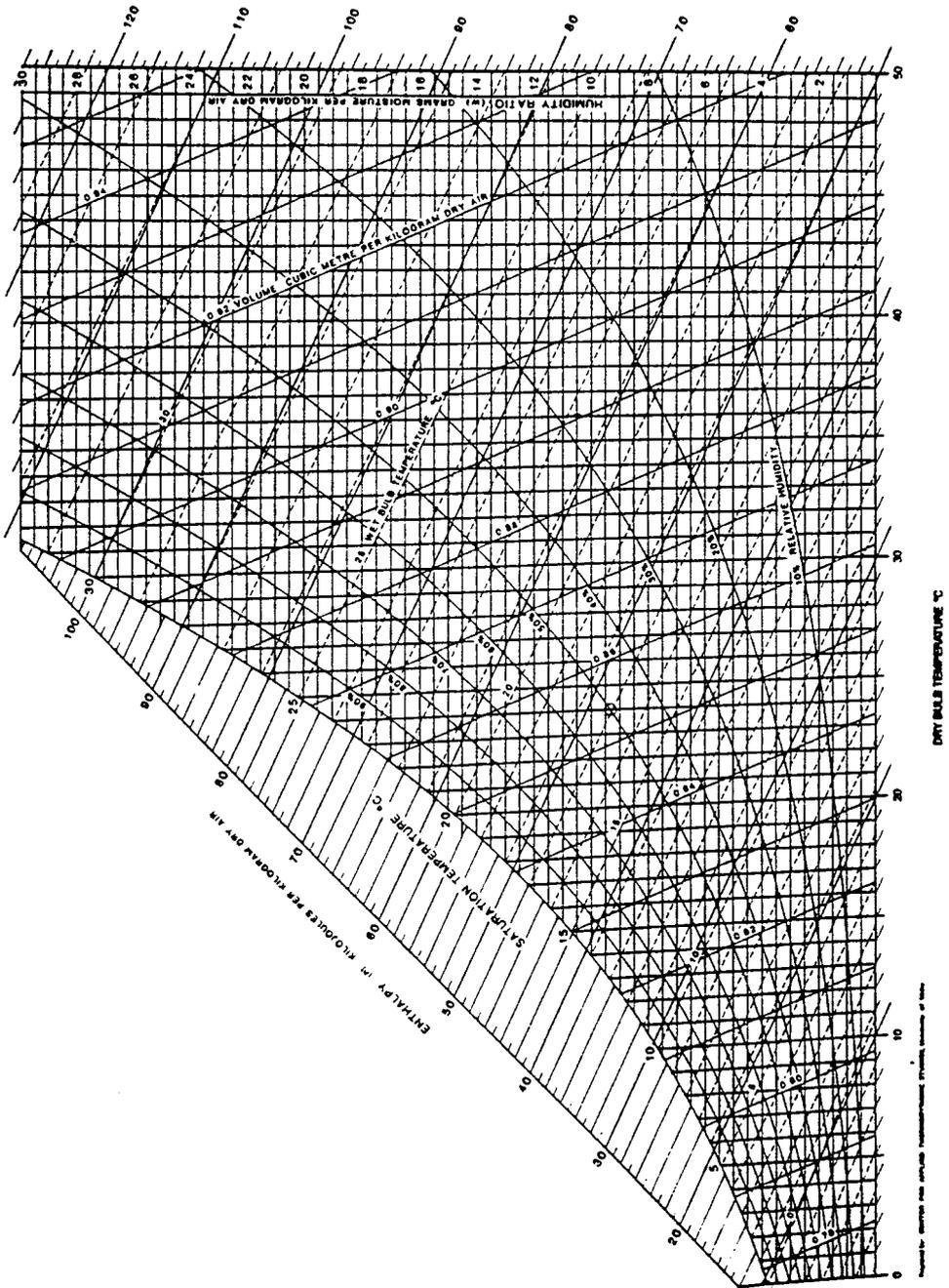


Figure 1.9. ASHRAE psychrometric chart in 0–50°C temperature range and at a barometric pressure of 101.325 kPa. (Copyright 1993 by the American Society of Heating, Refrigerating and Air-Condition Engineers, Inc.; reprinted with permission.)

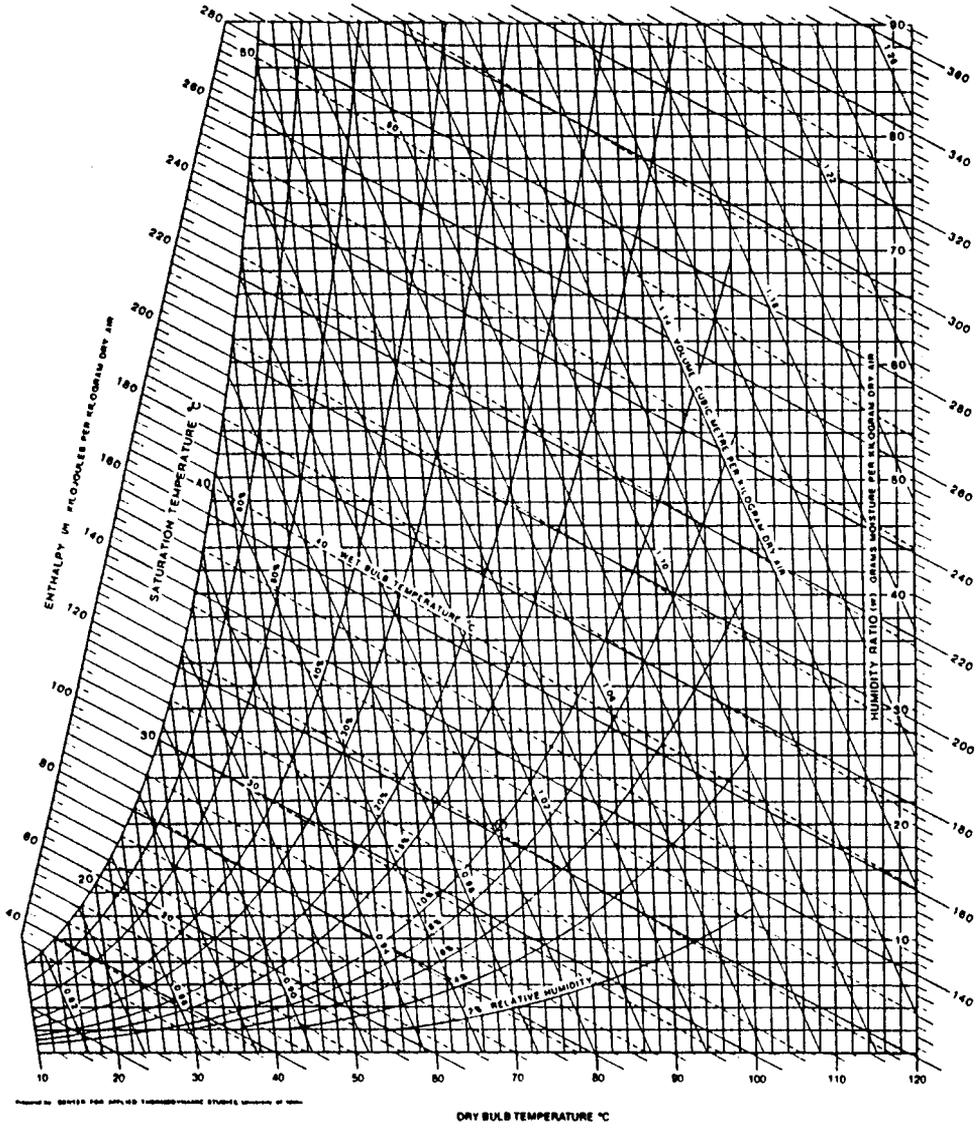


Figure 1.10. ASHRAE psychrometric chart in 10–120°C temperature range and at a barometric pressure of 101.325 kPa. (Copyright 1993 by the American Society of Heating, Refrigerating and Air-Condition Engineers, Inc.; reprinted with permission.)

Table 1.14. Equilibrium moisture content of selected grains at 25°C (percentage wet basis)

	20% Relative Humidity	40% Relative Humidity	60% Relative Humidity
Maize	7.1	10.0	12.4
Rough rice	6.5	9.4	12.2
Soybeans	5.3	6.9	9.7
Wheat (hard red)	7.2	9.9	12.1

Source: [2].

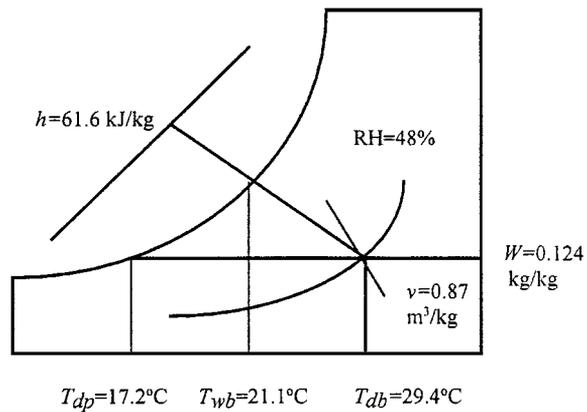


Figure 1.11. Illustration of the use of the psychrometric chart.

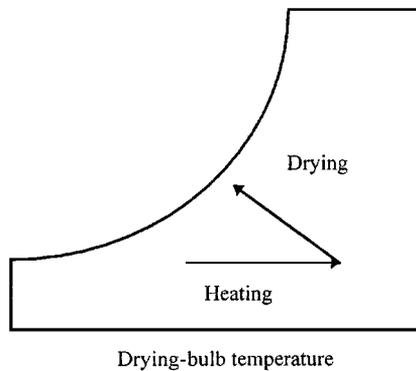


Figure 1.12. Representation on the psychrometric chart of the process of adiabatic drying.

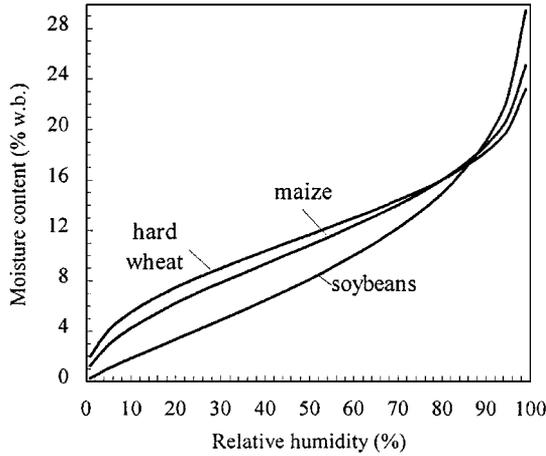


Figure 1.13. Equilibrium moisture-content curves of hard wheat, maize, and soybeans at 16.7°C. (Source: [1]).

The relationship between the EMC and the air conditions can be represented by the following empirical EMC equation:

$$M_{eq} = a - b \ln[-(T + c) \ln RH], \tag{1.1}$$

where a , b , and c are product constants, T is the temperature (°C), RH is the relative humidity (decimal), and M_{eq} is the equilibrium moisture constant (decimal dry basis). Table 1.15 contains the product constants in Eq. (1.1) for selected grains.

Airflow

As grain kernels lose moisture during the drying process, the evaporated water is carried by a flow of air from the grain bed in the form of water vapor. To properly design and operate a grain-drying system, the principles of air movement must be understood, especially as it relates to static pressure, fan characteristics, and system operating condition.

Table 1.15. Product constants for the equilibrium moisture content equation (Eq. [1.1]) of selected grains

	a	b	c
Maize	0.339	0.059	30.205
Rough rice	0.294	0.046	35.703
Soybeans	0.416	0.072	100.288
Wheat (hard red)	0.356	0.057	50.998

Source: [2].

Static Pressure

The *static pressure* of a grain drying system is mainly the resistance to the flow of air through the grain. The static pressure (ΔP) is expressed in Pascals per meter thickness of grain and can be calculated for a particular grain species by

$$\Delta P = \frac{aQ^2}{\ln(1 + bQ)}, \quad (1.2)$$

where a and b are product constants, and Q is the airflow rate in cubic meters per second per square meter of grain-layer area. Values for the product constants a and b are tabulated for selected grains in Table 1.16. The relationship between ΔP and Q is shown in graphical form for grains in Fig. 1.14. In a well-designed grain-drying system, over 90% of the resistance to the airflow occurs in the grain, and less than 10% in the airducts,

Table 1.16. Product constants for the static pressure equation (Eq. [1.2]) of selected grains

	a	b
Maize	2.07×10^4	30.4
Rough rice	2.57×10^4	13.2
Soybeans	1.02×10^4	16.0
Wheat (hard red)	2.70×10^4	8.8

Source: [1].

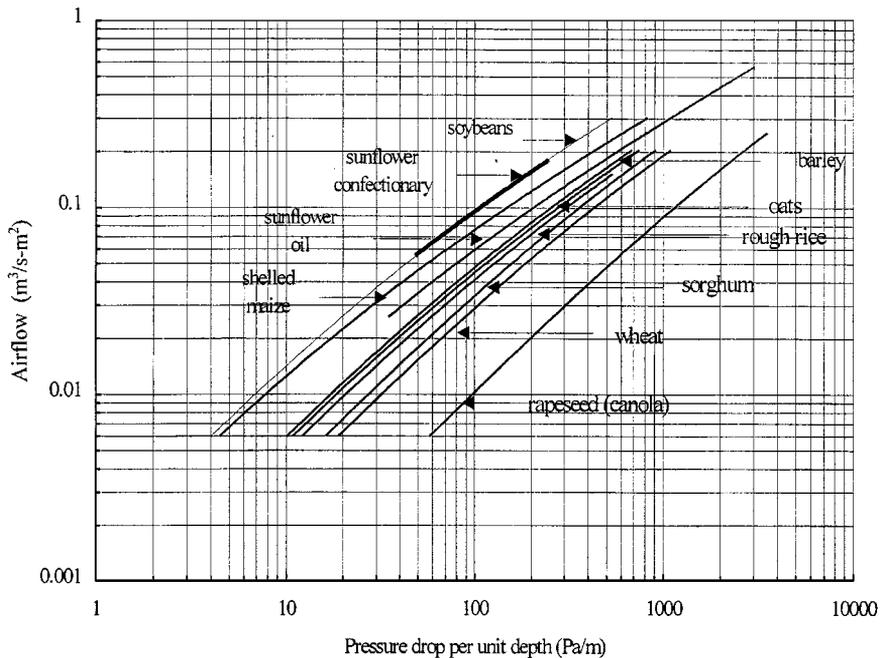


Figure 1.14. Airflow resistance of grains. (Source: [1]).

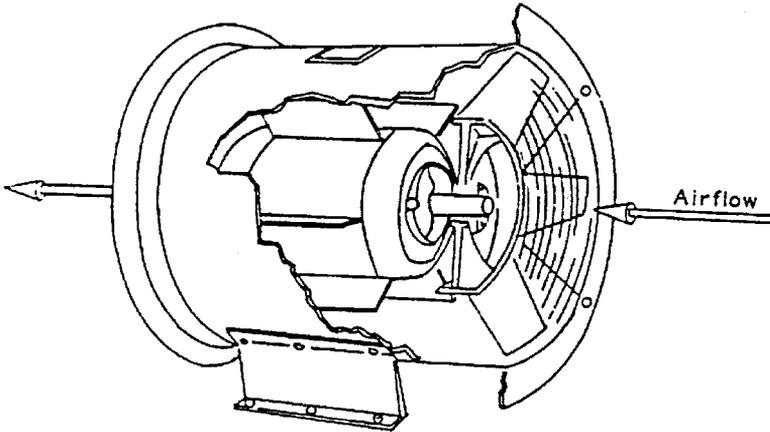


Figure 1.15. Typical axial-flow drying fan.

perforated floors, and grain-column screens [1]. The *system curve* of a grain-drying system is a plot of the total static pressure of the system versus the airflow rate.

Fans

The movement of air in a grain-drying system is caused by the operation of one or more fans. The two major fan types are the axial-flow type and the backward-curved centrifugal type.

In an axial-flow fan the air moves parallel to the fan axis and at a right angle to the field of rotation of the blades. An axial-flow fan is illustrated in Fig. 1.15.

In a centrifugal fan the air enters the housing parallel to the axis and is discharged perpendicular to the direction in which it enters the fan. A backward-curved centrifugal fan is shown in Fig. 1.16.

The characteristics of a fan can be expressed in a tabular form (see Table 1.17), by a fan curve (see Fig. 1.17), or by a fan equation (see Eq. [1.3]). A typical empirical fan equation that relates the airflow rate (Q) to the static pressure (ΔP) is:

$$Q = a + b\Delta P + c\Delta P^2, \tag{1.3}$$

where a , b , and c are fan-specific constants [1].

Table 1.17. Performance of three commercial backward-curved centrifugal fans (in cubic meters per minute)

Fan Power Rating (kw)	250-Pa Pressure	750-Pa Pressure	1250-Pa Pressure
7.5	359	314	266
11.2	475	423	368
15.0	543	505	453

Source: Shivers, Inc.

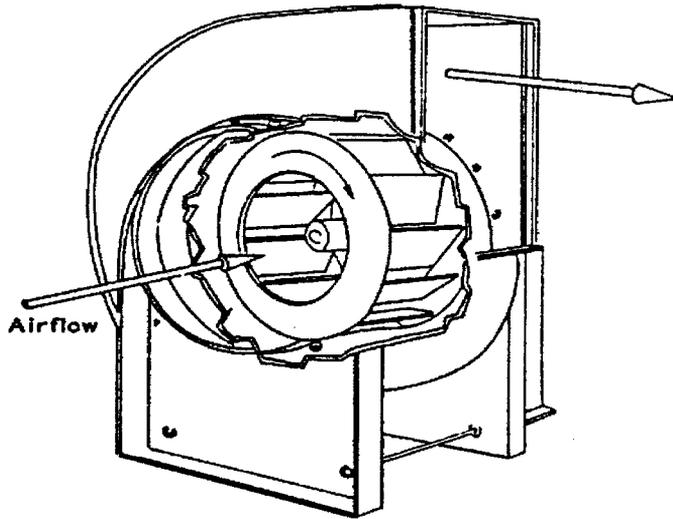


Figure 1.16. Typical centrifugal drying fan.

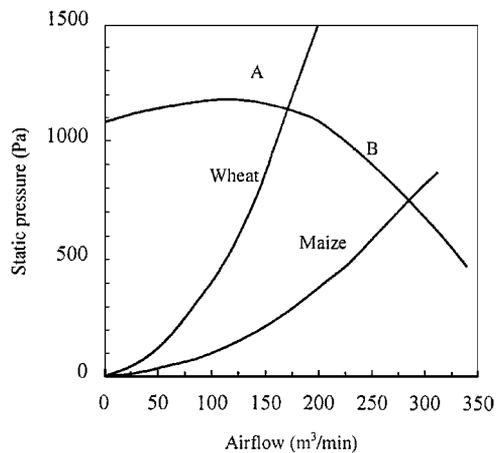


Figure 1.17. Operating conditions for an in-bin wheat-drying system and a maize-drying system.

Axial-flow fans usually deliver higher airflow rates than centrifugal fans of equal power at static pressures below 1000 Pa. If a grain system operates at static pressures above 1200 Pa, a centrifugal fan delivers the higher airflow rate. An axial-flow fan is noisier but less expensive than an equivalent centrifugal fan.

System Operating Condition

If the system curve and the fan curve of a grain-drying system are plotted on the same graph, the *operating condition* of the fan/drying system is located at the intersection of the two curves. This is illustrated in Fig. 1.17 for an in-bin system in which both maize

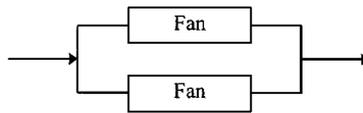
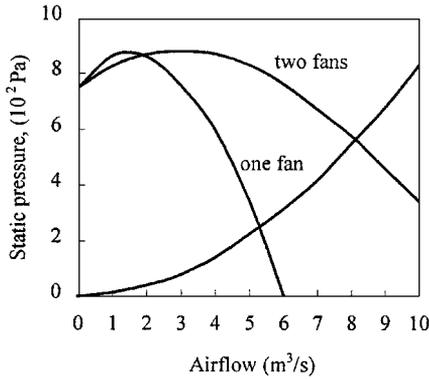


Figure 1.18. Performance of identical fans in parallel.

and wheat are dried. The axial-fan output for maize is 283 m³/min, but for wheat it is only 170 m³/min because of the larger static pressure of wheat.

On large grain silos, two fans frequently are placed in parallel in order to increase the airflow rate. (Only identical fans should be chosen for parallel installation.) The performance of a parallel-airflow system is shown in Fig. 1.18; the airflow characteristics of the system are found by adding the flowrate of the fans at a particular static pressure.

Drying Rate

The drying rate of grain in a grain-drying system depends on the drying rate of the individual grain kernels. In general, small kernels lose moisture more readily than large kernels, and naked seeds dry faster than covered seeds. This is illustrated in Fig. 1.19, in which the drying curves of maize, rice, and wheat at 49°C are drawn. Maize contains the largest kernels and dries the slowest; rice and wheat seeds are of comparable size but rice kernels are covered and therefore dry slower than wheat kernels.

Grain kernels dry at a falling rate. This is shown in Fig. 1.20, in which the drying and the drying-rate curves are drawn for a typical grain species. In Table 1.18 data are tabulated for the relative drying rates of several grains. As the kernels increase in size, and decrease in moisture content, the drying rate decreases.

Typical equations for the drying rate of the major grains follow.

Maize [4]

$$\begin{aligned}
 MR &= \exp(-kt^n) \\
 k &= 2.216 \times 10^{-2} + 1.113 \times 10^{-4}T + 3.435 \times 10^{-6}T^2 \\
 n &= 0.5409 + 1.498 \times 10^{-3}T + 2.561 \times 10^{-6}T^2
 \end{aligned}
 \tag{1.4}$$

Table 1.18. Relative drying rates of selected grains

	22% w.b. Moisture Content	18% w.b. Moisture Content	14% w.b. Moisture Content
Peas	95	35	15
Maize	135	50	15
Wheat	210	100 ^a	35
Canola	—	1150	500

Source: [3].

^a The drying rate of wheat at 18% moisture content is selected as 100.

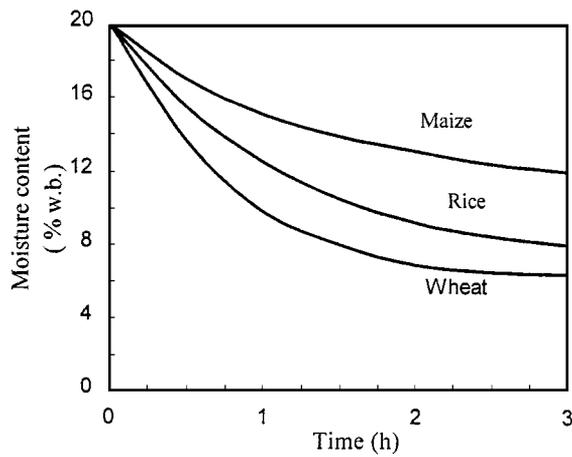


Figure 1.19. Comparison of drying rates of dent maize, medium rice, and soft wheat at 49°C.

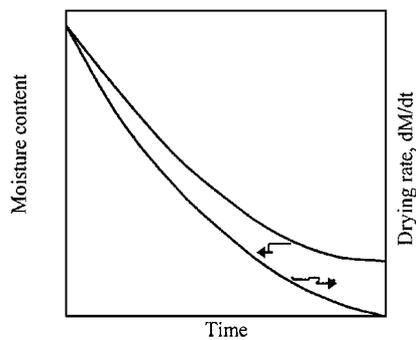


Figure 1.20. Grain drying during falling-rate period.

If the effect of initial moisture content is considered, then the equations become:

$$k = 1.091 \times 10^{-2} + 2.767 \times 10^{-6}T^2 + 7.286 \times 10^{-6}TM_o$$

$$n = 0.5375 + 1.141 \times 10^{-5}M_o^2 + 5.183 \times 10^{-5}T^2$$

where

t = time (min)
 T = air temperature, 27–116°C
 RH = relative humidity, 5%–40%
 M_o = initial moisture content, 23% to 36% d.b.
 V = airflow, 0.1–0.5 m³/s/m²

Medium-grain Rice [5]

$$MR = \exp(-kt^n)$$

$$k = 0.01579 + 1.746 \times 10^{-4}T + 0.01413RH$$

$$n = 0.6545 + 2.425 \times 10^{-3}T + 0.07867RH$$
(1.5)

where

t = time (min)
 T = air temperature, 30–55°C
 RH = relative humidity, 25%–95%

Soybeans [6]

$$MR = \exp(-kt^n)$$

$$k = 0.0333 + 0.0003T$$

$$n = 0.3744 + 0.00916T RH$$
(1.6)

where

t = time (min)
 T = air temperature, 32–49°C
 RH = relative humidity, 34% to 65%

Wheat [7]

$$MR = \exp(-kt)$$

$$k = 2000 \exp(-5049/(T + 273))$$
(1.7)

where

t = time (s)
 T = air temperature, 66–131°C

The drying-rate equations for other grains can be found in Ref. [8].

Drying Models

Drying models have been developed for each of the major dryer designs described in Sections 1.3.3 and 1.3.4. The models are based on the laws of heat and moisture transfer. The following is the in-bin grain drying model [1]:

$$\frac{\partial T}{\partial x} = \frac{-ha}{G_a(c_a + c_v W)}(T - \theta) \quad (1.8a)$$

$$\frac{\partial \theta}{\partial t} = \frac{ha}{\rho_p(c_p + c_w M)}(T - \theta) - \frac{h_{fg} + c_v(T - \theta)}{\rho_p(c_p + c_w M)}G_a \frac{\partial W}{\partial x} \quad (1.8b)$$

$$\frac{\partial W}{\partial x} = -\frac{\rho_p}{G_a} \frac{\partial M}{\partial t} \quad (1.8c)$$

$$\frac{\partial M}{\partial t} = \text{a thin-layer drying equation} \quad (1.8d)$$

Simultaneous solution of the four differential equations provides information on the grain moisture content (M) and temperature (θ), the air temperature (T), and the humidity ratio (W) as functions of bin location (x) and time (t). Note that the airflow rate (G_a) and the kernel properties (c_p , ρ_p , h_{fg}) each influence the changing moisture content distribution of the grain in the bin with time.

Simulation models for other grain-dryer designs can be found in [1].

1.3.2 Sun Drying

In many tropical and sub-tropical regions, *sun drying* remains the preferred method of grain drying, mostly for economic reasons. Traditional sun drying has changed little over the centuries. The grain is spread on mats or paved ground in layers of 5- to 15-cm thickness and is exposed to the ambient conditions. The grain is stirred intermittently, usually is covered at night, and dries adequately in 2 to 4 days.

The fixed costs of sun drying are low (except if a special drying floor has to be constructed). However, sun drying is an unreliable process because it is weather-dependent. Also, the solar radiation changes with the season and the time of day, and the flux density is low.

Notwithstanding its disadvantages, it is possible to produce dried grain of superior quality if sun drying is practiced competently. Of particular importance are the proper selection of the maximum layer thickness and the initial moisture content of the grain, and the recognition that during certain periods of the year (i.e., the wet season) adequate sun drying of grain is not feasible.

Notwithstanding the widespread use of the sun drying of grains in the developing world, few controlled scientific experiments have been conducted. Therefore, no general recommendations valid for every region can be made for the sun drying of grains.

Physics of Sun Drying

The sun drying of grain is affected by the solar radiation, the ambient air temperature, the ambient relative humidity, the wind velocity, the soil temperature, the grain-layer thickness, and the grain type. Simulation of the process [9] has resulted in a better

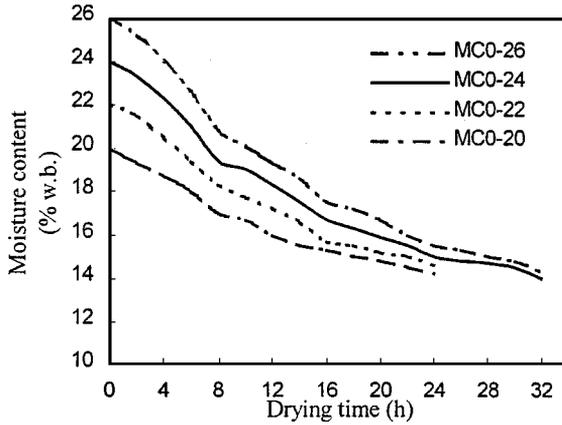


Figure 1.21. Average moisture content during sun drying of rice at different initial moisture contents.

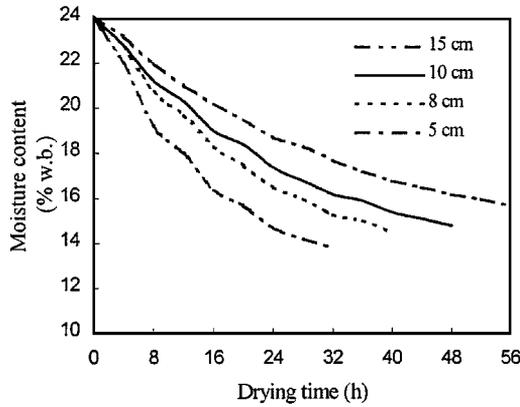


Figure 1.22. Rice-grain moisture content during sun drying with grain-bed depths of 5, 8, 10, and 15 cm.

understanding of sun drying, in particular of the effects of initial moisture content, layer thickness, and season on the drying process (see Figs. 1.21–1.23). The specific information in the three figures pertains to Jakarta (Indonesia), but the trends are valid for other locations.

1.3.3 In-store Drying

In-store (i.e., in-bin) grain drying commonly is practiced on the farm and usually employs ambient air or slightly heated air as the drying medium. The major in-store drying methods are illustrated in Fig. 1.24 [1]. The objective of in-store drying is to decrease the moisture content of the grain at a rate that will prevent product deterioration. Both the minimum drying rate and the maximum final moisture content are locality-dependent;

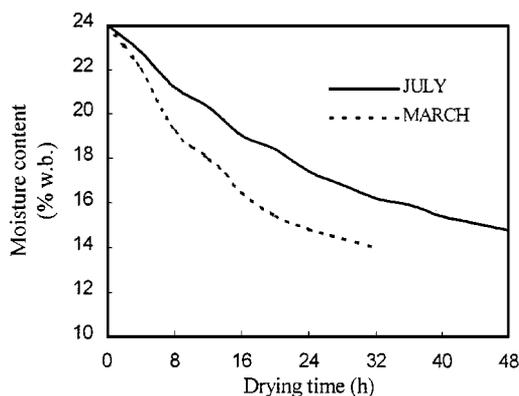


Figure 1.23. Moisture content of rice during sun drying in July and March.

that is, in hot and humid regions the drying rate of wet grain has to be higher, and the final moisture content lower, than in cold and dry areas.

Ambient/Low-temperature Drying

Drying a bin of grain with ambient air is possible if the initial moisture content of the grain is not excessive, the average daily relative humidity of the ambient air is not too high, and the airflow rate is sufficient. The recommended maximum initial moisture contents of maize and wheat, and the minimum airflow rates, for ambient-air drying under midwestern U.S. conditions are listed in Table 1.19. In the tropics, the initial moistures are lower and the required airflow rates are higher. The reader should obtain the exact values for a locality from the regional extension service.

In ambient-air *layer drying*, a bin is filled in stages; a wet layer is added only after the lower grain layers have been partially dried. In *stir drying*, one or more vertical stirring augers slowly move the dried grain from the bottom of the bin to the top, and the top grain layers to the bottom of the bin. Layer drying and stir drying require lower airflow rates and permit higher initial moisture contents than ambient-air drying.

In periods of zero drying potential during rain or high humidity, the relative humidity of the air can be decreased to the desired level (i.e., 60%–70%) by increasing the

Table 1.19. Characteristics of ambient air drying of several grains in the midwestern United States

	Moisture (% w.b.)	Airflow (m ³ /m ³ ·min)
Maize	20	2.4
Wheat	18	1.6
Wheat	16	0.8

Source: [1].

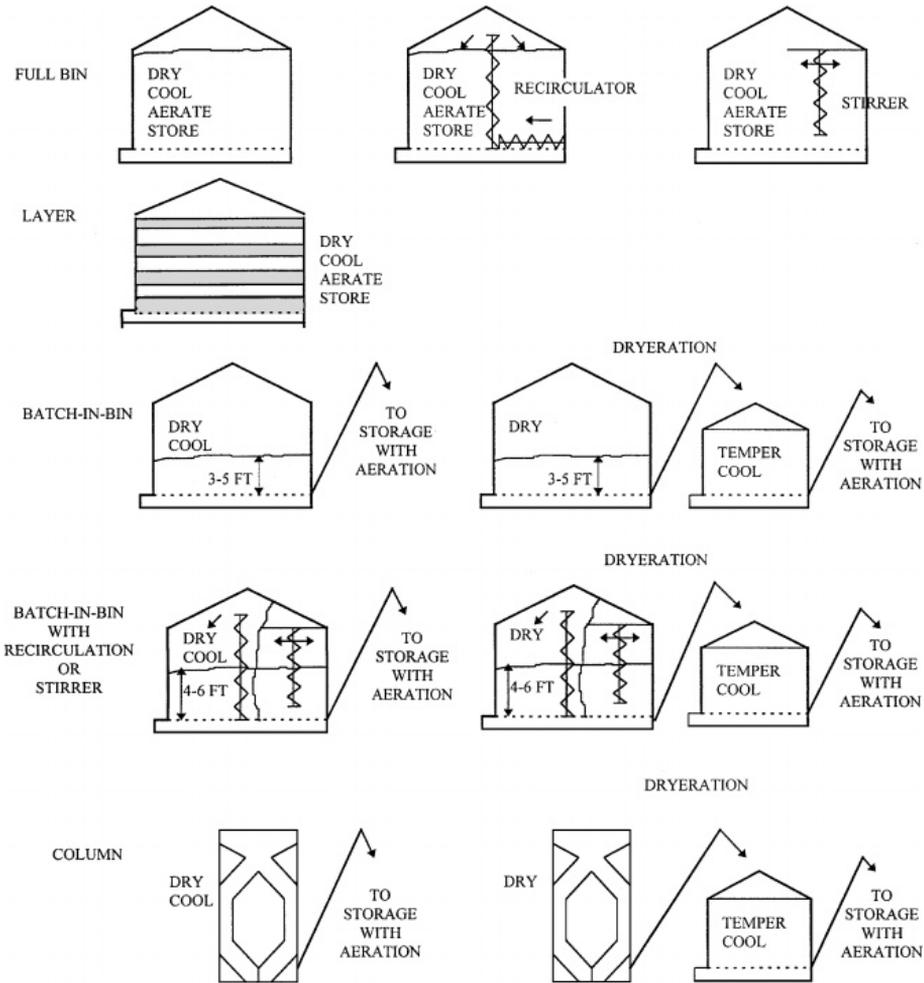


Figure 1.24. On-farm in-bin and non-bin grain-drying systems [1].

air temperature by 2 to 3°C. This process of in-bin drying frequently is called *low-temperature drying*. The airflow rate and maximum initial moisture content of the grain are similar for ambient and low-temperature drying. Stirrers are frequently employed in an in-store/low-temperature drying system.

A basic in-bin ambient-air/low-temperature grain dryer is shown in Fig. 1.25.

High-temperature Drying

A number of the in-store drying processes illustrated in Fig. 1.24 can be classified as high-temperature systems. The simplest design is the bin-batch dryer. A relatively shallow (1–1.5 m) layer of wet grain is dried at a temperature of 45 to 65°C and an airflow rate of 5 to 10 m³/(m³·min) in 8 to 12 hours depending on the initial moisture

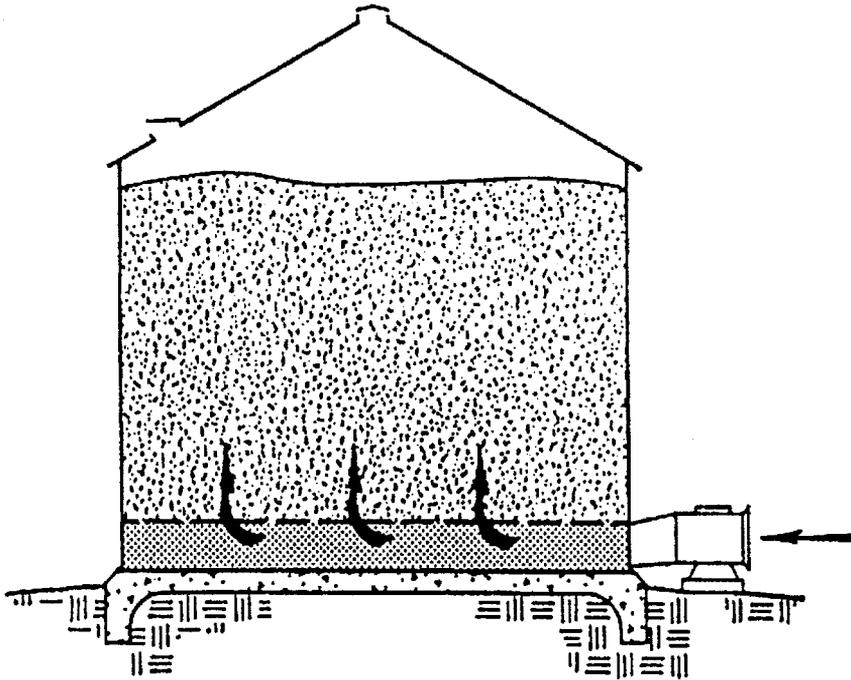


Figure 1.25. In-bin grain-drying system.

content. A major disadvantage of a bin-batch system is the overdrying of the bottom grain layers. Cooling of the grain requires 1 to 2 hours.

In the roof bin-batch dryer, the drying floor is elevated in the bin; the grain depth is limited to 0.5 m. The wet grain is partially dried at a relatively high temperature (60–80°C) and airflow rate (10–15 m³/(m³·min) before being dumped to the bottom of the bin, where the final drying and cooling of the grain occurs. The roof bin-batch system is a versatile system employed mainly for maize.

The in-bin counterflow drying process can operate as a grain-recirculating system, or as a continuous-flow system. Grain is continuously or intermittently loaded into a drying bin and is intermittently removed in thin layers by a tapered auger located at the bottom of the bin. The partially dried, hot grain is either recirculated to the top of the bin or moved to a second bin for slow in-bin final drying and cooling. The automatic nature of the process and the capability to produce high-quality grain at fairly high capacities have contributed to its commercial success. The airflow rate, bed depth, and drying-air temperature in in-bin counterflow dryers are similar to those in bin-batch systems; however, the in-bin counterflow systems produce dried grain of fairly uniform moisture gradient while bin-batch dryers do not.

Combination drying is a process in which high-temperature in-store or high-capacity drying is followed by low-temperature, low-capacity in-bin drying and cooling (see Fig. 1.24). Combination drying mainly is used for maize and rice; it is also called, a

combination of the terms drying and aeration. In a combination-drying system, wet grain is dried from 22% to 28% moisture in a high-temperature dryer to an intermediate moisture content of 18% to 20% and then moved hot to an in-bin dryer. After tempering for 6 to 8 hours, it is slowly final-dried and cooled with ambient air. The main advantages of combination drying are the increased drying capacity and the improved energy efficiency and grain quality.

In-bin Dryer Controls

It may be economically advantageous to operate the fan on an ambient-air/low-temperature drying system, and on a silo-aeration system, intermittently because of favorable or nonfavorable weather conditions. The hardware of the two controller types is similar, but their software differs.

In-bin control systems usually measure the temperature and relative humidity of the ambient air and the temperature of the grain. Some controllers also measure the relative humidity of the air in the interstices of the grain mass. The proper location of sensors in the bin is critical. Control actions are based on the maximum temperature and equilibrium relative humidity of the grain, and thus the sensors should be located where these values are likely to occur, namely in the center of the bin under the loading spout. Multiple sensors increase the chance of detecting a hot spot; the choice of the number of sensors is an economic compromise.

Modern in-bin controllers are equipped with microprocessors that allow the user to change the strategy of the control action. Following is a list of a number of performance criteria for in-store drying (and aeration) [10, 11].

- Minimize fan operation (h)
- Minimize overdrying (% , w.b.)
- Minimize moisture content range (% , w.b.)
- Minimize time to finish drying (h)
- Minimize average dry matter loss (%)
- Minimize cost of overdrying (\$/tonne)
- Minimize cost of energy usage (kwh/tonne)
- Minimize net cost (\$/tonne)

It is clear that all eight of the criteria cannot be minimized simultaneously. Thus, the manager of a grain depot has to decide which performance criterion should be minimized before a microprocessor is programmed.

1.3.4 High-capacity Drying

High-temperature dryers are employed for the drying of grains if high drying capacities are required. These dryers are unable to produce grains of the same high quality as low-temperature in-bin drying systems. However, in many cases a slight decrease in grain quality is acceptable to the end-user of the grain.

The three major high-temperature dryer types are cross-flow dryers, mixed-flow dryers, and concurrent-flow or counterflow dryers. A schematic of each type is illustrated in Fig. 1.26, and the moisture content and temperature distribution of the grain in each is

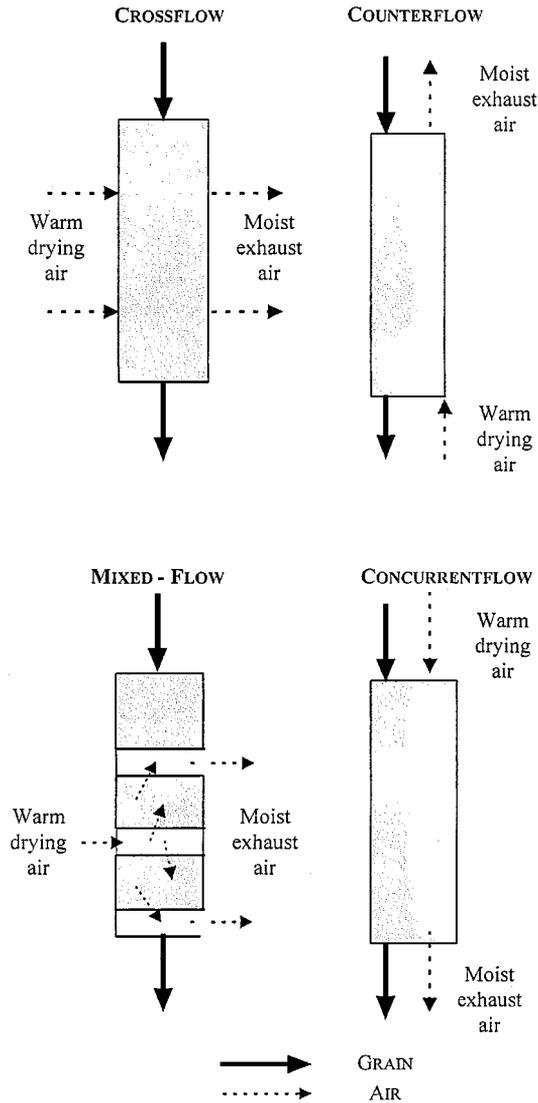


Figure 1.26. Schematics of the four major types of high-temperature grain dryers: cross-flow, counterflow, concurrent-flow, and mixed-flow.

shown in Fig. 1.27. The air and grain move in *perpendicular* directions in crossflow dryers, in the *same* direction in concurrent-flow dryers, in *opposite* direction in counterflow coolers, and in a *combination* of cross-flow, concurrent-flow, and counterflow directions in mixed-flow dryers. In theory, the variation in moisture content and temperature, and thus in grain quality, in a sample of dried grain is substantial in cross-flow dryers, less in mixed-flow dryers, and almost nonexistent in concurrent-flow or counterflow dryers.

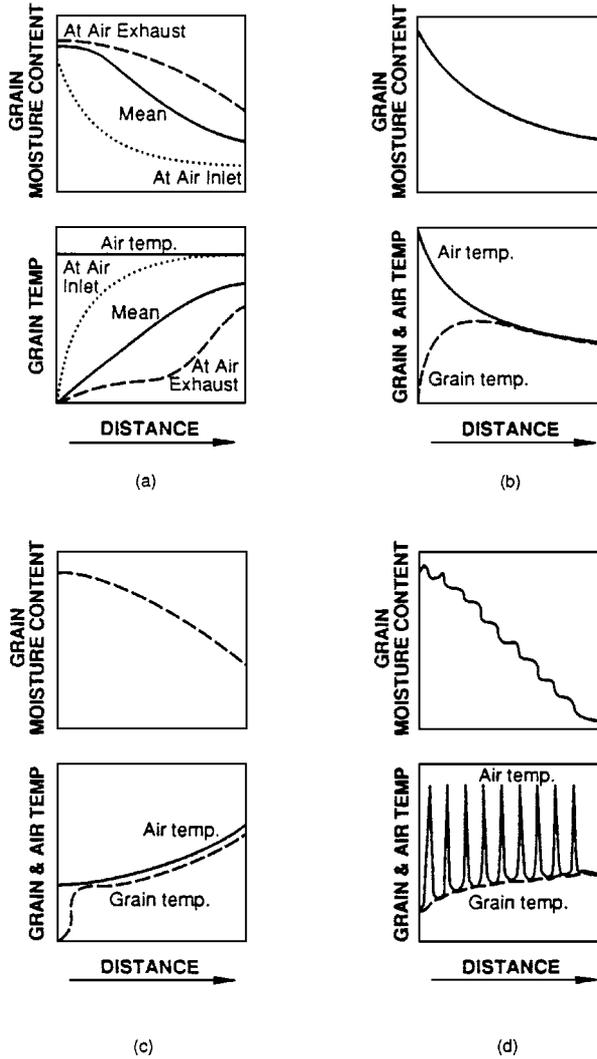


Figure 1.27. Moisture and temperature changes during cross-flow drying (a), concurrent-flow drying (b), counterflow drying (c), and mixed-flow drying (d).

High-temperature dryers contain a cooling section in which the hot grain after moving through the drying section is reduced in temperature to within 3 to 5°C of the ambient temperature. Grain remains in the cooling section of a dryer about half as long as in the drying section.

Cross-flow Dryers

Figure 1.28 illustrates a cross-flow grain dryer. The wet grain flows by gravity from a wet holding bin through screened grain columns surrounding the plenum. A heater-fan

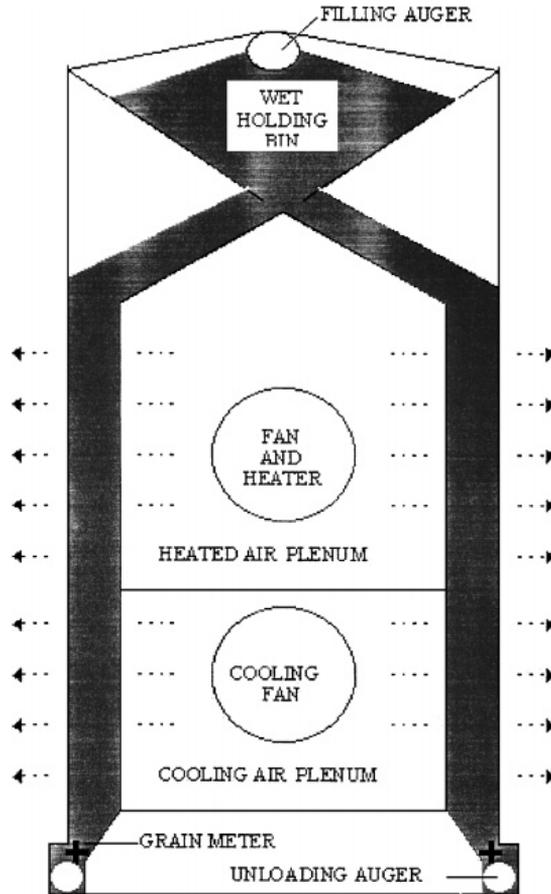


Figure 1.28. Conventional cross-flow dryer with forced-air drying and cooling.

assembly is located within the drying section of the heated air plenum and forces the hot air through the grain to the ambient in a direction perpendicular to the flow of the grain. In the cooling section of the dryer, ambient air is drawn by cross-flow through the grain into the heater-fan assembly.

Table 1.20 contains the specifications of a typical commercial cross-flow maize dryer.

Mixed-flow Dryers

Figure 1.29 is a schematic of a mixed-flow grain dryer. The wet grain flows from a garner bin over alternate horizontal rows of hot inlet-air ducts and cold outlet-air ducts. The spacing between the airducts determines the grain-layer depth through which the air is forced. Air from the inlet-air ducts flows upwards and downwards to the surrounding outlet-air ducts, in a combination of cross-flow, concurrent-flow, and counterflow with respect to the grain. The bottom series of inlet-air and outlet-air ducts in a mixed-flow

Table 1.20. Specifications of a typical commercial cross-flow maize dryer

Characteristic	Specification
Airflow, heat section	$79 \text{ m}^3 \text{ min}^{-1} \text{ ton}^{-1}$ $18.6 \text{ m}^3 \text{ m}^{-2} \text{ min}^{-1}$
Airflow, cooling section	$147 \text{ m}^3 \text{ min}^{-1} \text{ ton}^{-1}$ $33.8 \text{ m}^3 \text{ m}^{-2} \text{ min}^{-1}$
Static pressure, heat section	0.37 kPa
Static pressure, cooling section	0.37 kPa
Column cross-sectional area	6.5 m^2
Column width	0.3 m
Grainflow at 5 point moisture removal	$26.8 \text{ m} \cdot \text{h}^{-1}$
Recommended drying temperature	82.2°C
Rated capacity at 15%–20% moisture content	$127 \text{ ton} \cdot \text{h}^{-1}$
Retention time at rated capacity	1 h
Burner capacity	$57.2 \times 10^6 \text{ kJ} \cdot \text{h}^{-1}$

Source: [1].

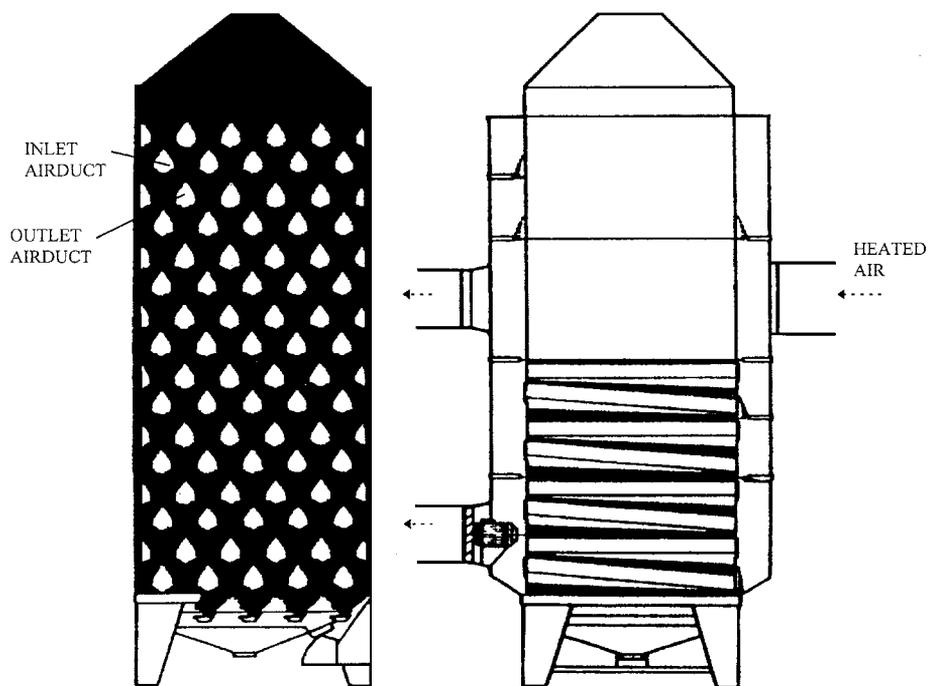


Figure 1.29. A mixed-flow grain dryer. (Source: Cimbría Unigrain, Ltd.)

Table 1.21. Specifications of a typical commercial mixed-flow wheat-and-barley dryer

Characteristic	Specification
Overall height	12.74 m
Number of standard modules	8
Cross-sectional area	5.44 m ²
Holding capacity	27 ton
Capacity at 4% moisture removal	14.5 ton/h
Drying air temperature	68°C
Airflow	68000 m ³ /h
Heat consumption	760 × 10 ³ kcal/h

Source: Cimbria Unigrain Ltd., Denmark.

dryer serves as the cooling section. Table 1.21 contains the specifications of a typical commercial mixed-flow maize dryer.

Concurrent-flow Dryers

Figure 1.30 shows a schematic of a two-stage concurrent-flow grain dryer. A tempering section separates the two adjoining drying stages. The wet grain flows from a garner bin through the two drying sections and the tempering section in the same direction as the drying air. There is no airflow in the tempering section. (The function of the tempering process is to reduce the temperature and the moisture gradients in the kernels before subsequent further drying, and thus improve the grain quality.) In the cooler, the grain and air flow in opposite directions. The depth of the grain bed (or layer) in a concurrent-flow dryer and the static pressure and inlet-air temperature are substantially larger and higher than in cross-flow and mixed-flow dryers. Table 1.22 contains the specifications of a typical commercial concurrent-flow maize dryer.

Continuous-flow Dryer Controls

The moisture content of wet grain reaching a high-temperature continuous-flow dryer over a 24-hour period can vary greatly. At commercial elevators, it is not unusual to encounter moisture-content differences of 10% to 15% in lots of maize received from different growers. All the grain must be dried to approximately the same average moisture content, however, by properly varying the speed of the unload auger and thus the residence time of the grain in the dryer.

Manual control of continuous-flow dryers often leads to significant overdrying or underdrying because manual-control decisions in changing the auger speed are based on hourly readings of the inlet and outlet moisture contents of the grain. Automatic controllers receive this information continuously and thus can minimize the overdrying or underdrying of the grain.

For many years, the automatic control of continuous-flow grain dryers was limited to temperature-activated feedback-type controllers that measure the grain or the exhaust-air temperature at one or several locations along the drying column. A temperature-activated controller is inaccurate and inconsistent at moisture content changes exceeding 3%, due to the nonlinearity of the drying process. Therefore, the temperature-activated controllers are slowly being replaced by moisture-activated systems.

Table 1.22. Specifications of a typical commercial three-stage concurrent-flow maize dryer with counterflow cooler

Characteristic	Specification
Bed area	13.38 m ²
Capacity at 15%–24% moisture content	45 ton·h ⁻¹
Grain-flow velocity	4–7 m·h ⁻¹
Inlet moisture content	24% w.b.
Depth of each drying stage	0.76 m
Depth of each tempering stage	3 m
Depth of cooling stage	1.2 m
Airflow for each drying stage	570 m ³ min ⁻¹
Static pressure in drying stage	3.2 kPa
Airflow for cooling stage	570 m ³ min ⁻¹
Static pressure in cooling stage	2.4 kPa
Drying air temperature ^a	200°C
Fuel consumption	3933 kJ·kg ⁻¹

Source: [12].

^a Drying air temperature can be as high as 230–285°C.

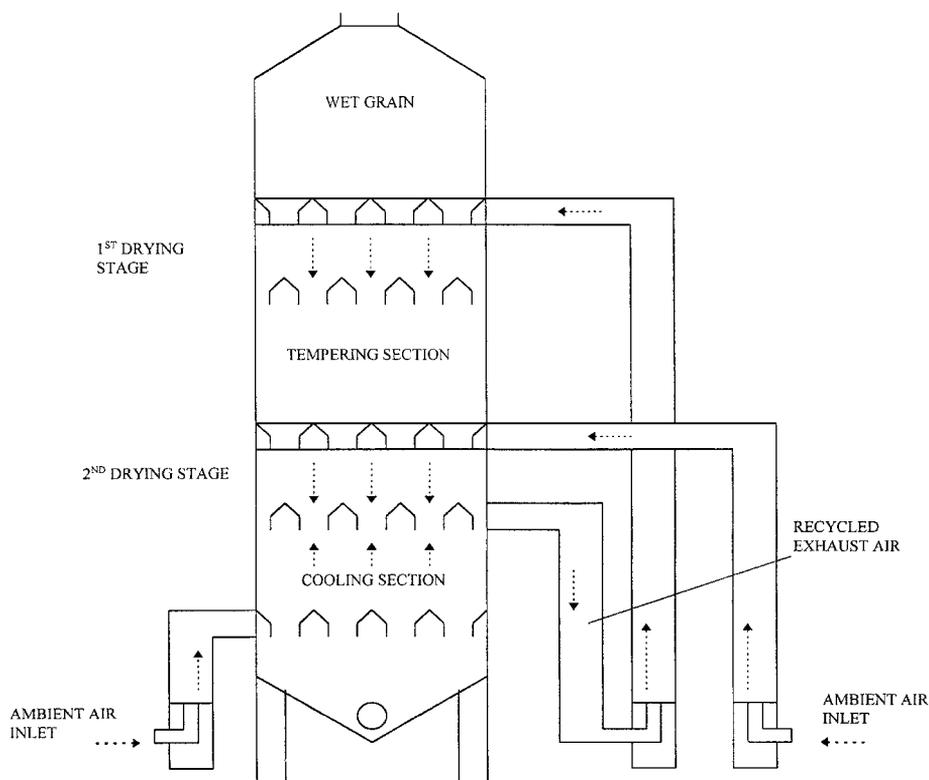


Figure 1.30. Two-stage concurrent-flow dryer with counterflow cooler, tempering section, and recirculation of the cooling air and part of the drying air [12].

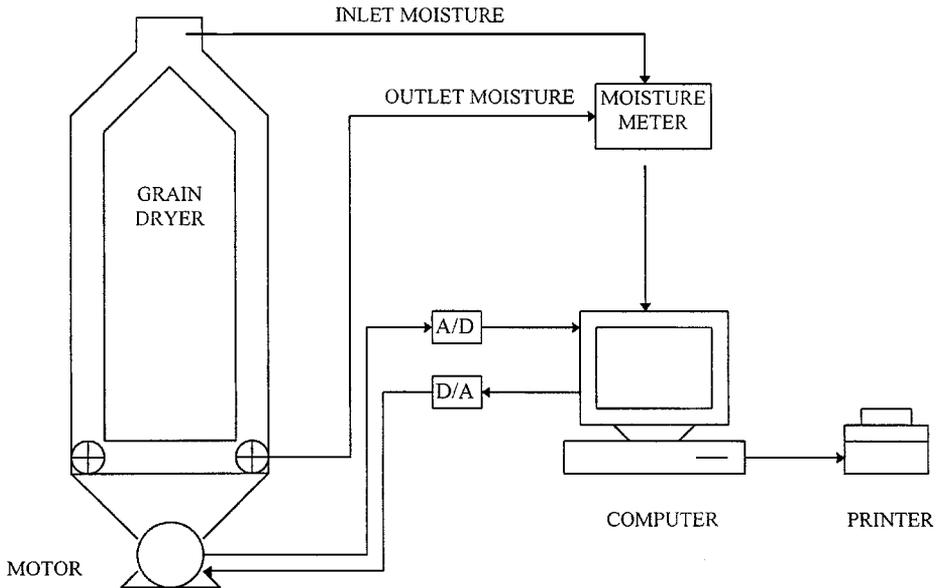


Figure 1.31. Schematic of an automatic control system for continuous-flow grain dryers. A/D, analog to digital; D/A, digital to analog.

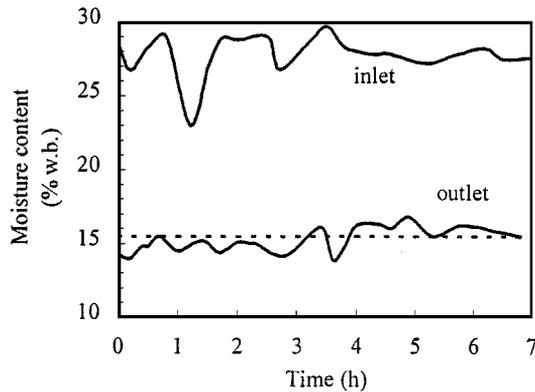


Figure 1.32. Inlet and outlet moisture contents versus time during a typical test of automatic control of a cross-flow maize dryer with a set point of 15.5% (w.b.).

Figure 1.31 shows the schematic of a moisture-based automatic control system installed on a high-capacity continuous-flow grain dryer. Figure 1.32 illustrates the variation in the outlet moisture content of maize dried in a cross-flow dryer operating under feedforward/feedback control [13].

1.3.5 List of Symbols

EMC equilibrium moisture content, dry basis (decimal)

G_a	airflow rate ($\text{kg dry air}\cdot\text{h}^{-1}$)
M	moisture content, dry basis (decimal)
MR	moisture ratio $(M - M_{eq})/(M_o - M_{eq})$
ΔP	static pressure ($\text{Pa}\cdot\text{m}^{-1}$)
Q	airflow rate ($\text{m}^3 \text{ m}^{-2} \text{ s}^{-1}$)
RH	relative humidity (decimal)
T	air temperature ($^{\circ}\text{C}$)
W	humidity ratio ($\text{kg}\cdot\text{kg}^{-1}$)
a, b, c	constants
c	specific heat ($\text{J}\cdot\text{kg}^{-1} \cdot ^{\circ}\text{C}^{-1}$)
h	enthalpy of moist air (kJ/kg)
ha	volume convection heat-transfer coefficient ($\text{J}\cdot\text{m}^{-3} \cdot ^{\circ}\text{C}^{-1}\cdot\text{h}^{-1}$)
h_{fg}	heat of evaporation ($\text{J}\cdot\text{kg}^{-1}$)
k, n	coefficient
t	time (h, min, or s)
v	specific volume of moist air ($\text{m}^3 \text{ kg}^{-1}$)
x	bed coordinate (m)
θ	grain temperature ($^{\circ}\text{C}$)
ρ	density ($\text{kg dry matter}\cdot\text{m}^{-3}$)

Subscripts:

a	air
dp	dew point
eq	equilibrium
o	initial
p	grain
v	vapor
w	water
wb	wet-bulb

References

1. Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1992. *Drying and Storage of Grains and Oilseeds*. New York: Van Nostrand Reinhold.
2. D245.4: Moisture relations of grains. 1991. In *ASAE Standards, 38th ed.* St. Joseph, MI: ASAE.
3. Kreyger, T. 1972. Drying and storing grains, seeds and pulses in temperate climates. Publication 205. Wageningen, The Netherlands: IBVL.
4. Li, H., and R. V. Morey. 1984. Thin-layer drying of yellow dent corn. *Trans. ASAE* 27:581–585.
5. Wang, C. Y., and R. P. Singh. 1978. A single layer drying equation for rough rice. Paper No. 78-3001. St. Joseph, MI: ASAE.
6. White, G. M., T. C. Bridges, O. J. Loewer, and I. J. Ross. 1981. Thin-layer drying model for soybeans. *Trans. ASAE* 24:1643–1646.
7. O'Callaghan, R., D. J. Menzies, and P. H. Bailey. 1971. Digital simulation of agricultural drier performance. *J. Agric. Eng. Res.* 16:223–244.

8. Jayas, D., S. Cenkowski, S. Pabis, and W. E. Muir. 1991. Review of thin-layer drying and wetting equations. *Drying Technology* 9:551–588.
9. Suhargo, and F. W. Bakker-Arkema. 1993. Sun-drying of grain. FAO Technical Symposium on Grain Drying and Storage in Latin America, Paper No. IV-4. Porto Alegre, R. S., Brasil.
10. Lynch, B. E., and R. V. Morey. 1989. Control strategies for ambient air corn drying. *Trans. ASAE* 32:1727–1736.
11. Peart, R. M., Y. C. Li, and J. R. Barrett. 1985. Simulation of a computerized grain drying decision support system. Paper No. 85-3014. St. Joseph, MI: ASAE.
12. Bakker-Arkema, F. W., and R. Hines. 1993. Concurrent-flow drying of maize under Chinese conditions. In *Proc. '93 Int. Symp. of Grain Drying and Storage Technology*, Beijing, China.
13. Moreira, R. G., and F. W. Bakker-Arkema. 1990. A feedforward/feedback adaptive controller for commercial cross-flow grain dryers. *J. Agric. Eng. Research* 45:107–116.

1.4 Grain Storage

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The objective of grain storage is to maintain the quality of the grain during the storage period, either short-term (i.e., 2–6 weeks) or long-term (i.e., over 4–8 weeks). The quality factors to be preserved (see Section 1.1) depend on the requirements of the end user of the grain.

To keep grain in good condition, it should be stored at a relatively low moisture content and cool temperature in order to prevent the development of molds and insects.

The practice of crib storage of ear maize and bag storage of grains still is exercised on smaller farms in many developing countries, but bulk storage is rapidly replacing both methods worldwide.

1.4.1 Crib Storage

The use of wire-cage cribs (Fig. 1.33) for the storage of ear maize is rarely practiced. Ear maize can be safely stored with natural ventilation at 20% to 25% moisture (w.b.) in temperate climates if excessive foreign matter (i.e., husks and silks) is absent. In warm and humid regions, cribs must permit fumigation to control insect infestation.

Proper ventilation can generally remove 3% to 5% excess moisture; therefore, high-moisture (>25% w.b.) ear maize can be stored with mechanical ventilation. An airflow rate of 5.6 to 11.1 m³ min⁻¹ ton⁻¹ is recommended for the safe storage of high-moisture ear maize [1].

1.4.2 Bag Storage

Bag storage of grains is suitable for small-scale systems in some regions of the world [2]. Bag storage has the advantage that the grain can be moved easily, and segregated in individual farmers' lots. Bags may be piled under any shelter and can be handled without

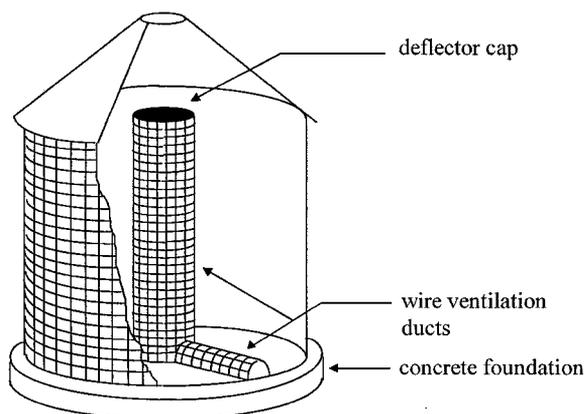


Figure 1.33. Cylindrical wire-cage crib.

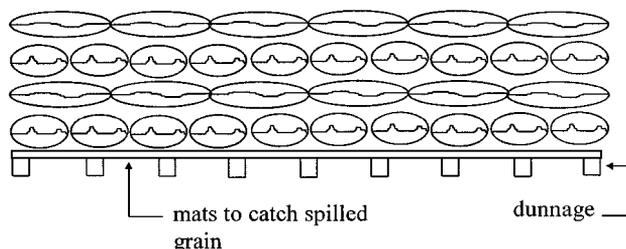


Figure 1.34. Typical bag-storage stacking pattern.

special equipment. Bag storage can become overly expensive in locations in which labor costs are high.

Bags typically made of woven jute, hemp, local grass, or cotton offer no protection against moisture, insects, and rodents. Polypropylene bags are mechanically stronger and are rodent-proof but are expensive and susceptible to deterioration by ultraviolet radiation. Jute bags can be stacked up to a height of 6 m in warehouses, polypropylene bags only to 3 m because of slipping.

Dunnage should be used to keep grain bags at least 15 cm off the floor (see Fig. 1.34). Stack size should not exceed 6×9 m, and a stack should be divided into six blocks containing 256 bags, with a row of six bags lengthwise adjacent to a row of 10 bags widthwise.

1.4.3 Bulk Storage

Vertical Storage

Grains commonly are stored in vertical structures, in particular in reinforced concrete silos and in steel bins. An economical layout of the various silos and bins is essential [3]. The foremost advantage of vertical storage is the efficient discharge of the grain

Table 1.23. Holding capacity of round bins/silos (in tons per meter of depth^a)

Diameter (m)	Maize	Wheat
4.57	11.8	12.8
5.49	17.0	18.5
6.40	23.1	25.1
7.32	30.3	32.9
8.23	38.3	41.6
9.14	47.2	51.3
10.06	57.2	62.1
10.97	68.0	73.8
11.89	79.9	86.7
12.80	92.6	100.5
14.63	120.9	131.3
18.29	189.0	205.3

Source: [4].

^a Does not include space above eave line. Based on 1.39 m³/ton for maize and 1.28 m³/ton for wheat.

by gravity flow. The structural-design requirements of silos and bins are discussed in Volume 2 of the CIGR Handbook.

The approximate holding capacities of round bins and silos with different diameters for maize and wheat in tons per meter depth is tabulated in Table 1.23. The exact holding capacity depends on the bulk density of the grain.

Concrete and metal each have advantages and disadvantages as basic construction materials for grain bins. The main benefits of concrete are long lifetime, limited maintenance, large storage volume, low thermal conductivity, and limited water-condensation problems. Drawbacks of the concrete grain silo are the significantly higher initial cost and erection time than those of steel bins of equal storage volume.

Steel bins have gained popularity rather recently. In addition to their advantages over concrete silos with respect to initial costs and erection time, steel bins are more easily accessible through manholes and are more easily fitted with aeration equipment and temperature-measuring instrumentation.

Concrete silo walls typically have a thickness of 150 mm; the thickness of steel bin walls is characteristically 5 mm. Thus, concrete and steel bins of the same outside diameter differ in volume; e.g., a 30 m high, 5 m diameter steel bin has a volume which is 12% greater than a concrete silo of equal dimensions [3].

Steel bins should be galvanized, and the bolts and nuts zinc coated; rust-protection paint should be applied when rust spots appear. The outside walls of concrete silos require a protective coating occasionally to prevent the damaging effect of environmental sulfurous air-pollution.

Horizontal Storage

Horizontal sheds and warehouses are often employed in addition to bins and silos for grain storage at large grain depots. It is more costly and labor-intensive to move grain

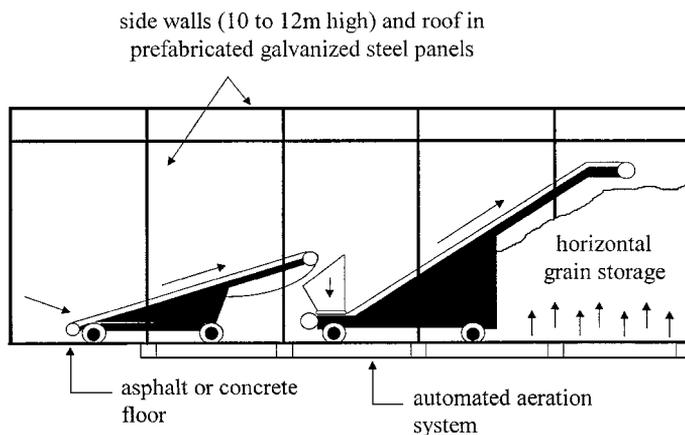


Figure 1.35. A horizontal grain-storage facility with aeration system in the ground [3].

into and out of a horizontal storage but the fixed cost per unit volume is significantly less for horizontal storage than for vertical storage.

The airflow during the aeration of grain in a shed is less uniform than in a bin, and therefore the airflow rate has to be higher, i.e. $0.05 \text{ m}^3 \text{ min}^{-1} \text{ ton}^{-1}$ i.s.o. $0.02 \text{ m}^3 \text{ min}^{-1} \text{ ton}^{-1}$. The maximum height of the grain in horizontal storages depends on the strength of the walls, but usually does not exceed 6–8 m.

A typical flat bottom warehouse is shown in Fig. 1.35; the aeration system is located in the concrete floor [3]. Note the conveying systems for filling the storage.

CA Storage

Controlled-atmosphere (CA) storage of grains includes commodity-modified CA storage and artificially modified CA storage [5]. In commodity-modified storage, respiration of the grain and the microorganisms reduces the O_2 and increases the CO_2 . The atmosphere in an artificially modified storage is changed by injecting N_2 or CO_2 into the system.

Traditional underground pit storage is an example of sealed commodity-modified CA storage; ideally, the O_2 decreases to 0.2% to 0.5% and the CO_2 increases to 45% to 50%. In such atmospheres, the toxin development of fungi and growth of insects are inhibited. Pit storage continues to be practiced in some developing countries, in particular in Africa [Dunkel, F., personal communication].

Nitrogen-producing exothermic generators are available commercially for altering the intragranular gas composition in a grain storage. They are employed mainly to prevent insect development during long-term storage of 12% to 14% moisture-content grains. Subjection to pure N_2 for a few days kills all forms of insects (i.e., eggs, larvae, adults), but it is difficult to maintain a storage without leakage. Therefore, many N_2 storages contain a gas mixture of 97% to 99% N_2 and 0.5% to 4% O_2 . At the lower N_2 levels, the lethal response of insects is negatively affected as the figures in Table 1.24 show. The

Table 1.24. Days of exposure to low oxygen levels in nitrogen required for complete control of adult insects in grain stored at 14–17°C

Species	<1% O ₂	1–2% O ₂	2–4% O ₂
<i>Oryzaephilus surinamensis</i>	10	7	18
<i>Sitophilus granarius</i>	12	15	27
<i>Tribolium confusum</i>	2	—	—

Source: [6].

exact response depends on the insect species, the grain temperature, and the moisture content [7].

Another gas employed for the CA storage of grains is CO₂ [8, 9].

Chilled Storage

To prevent the invasion of insects to non-CA stored grain, especially in the tropics and subtropics, the grain is treated with chemicals or lowered in temperature. The use of chemicals is discussed in the next subsection.

A grain chiller is a device that cools ambient air to the desired temperature and relative humidity before forcing the conditioned air through the stored grain (see Fig. 1.36). The grain chiller is basically a mechanical refrigeration unit equipped with a precise temperature and humidity controller. Figure 1.37 shows the level of control of the air temperature and humidity established by a chiller.

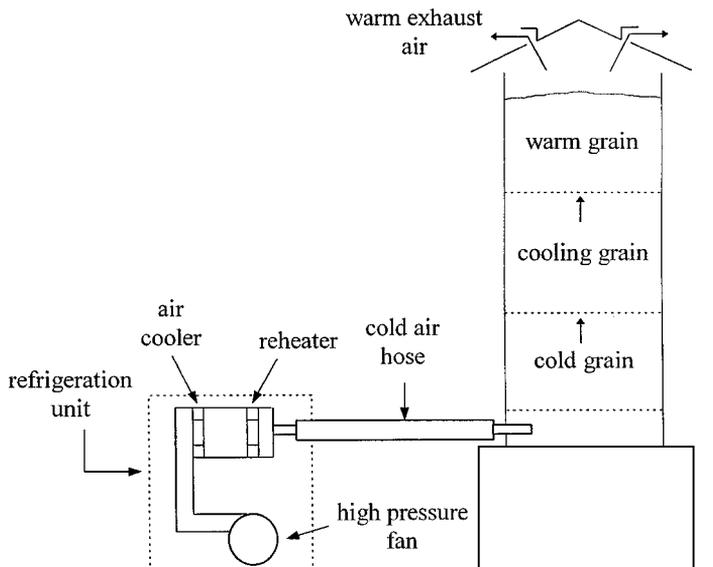


Figure 1.36. Grain-chilling process that utilizes a refrigeration system to control the temperature and relative humidity of the air before it enters the grain silo.

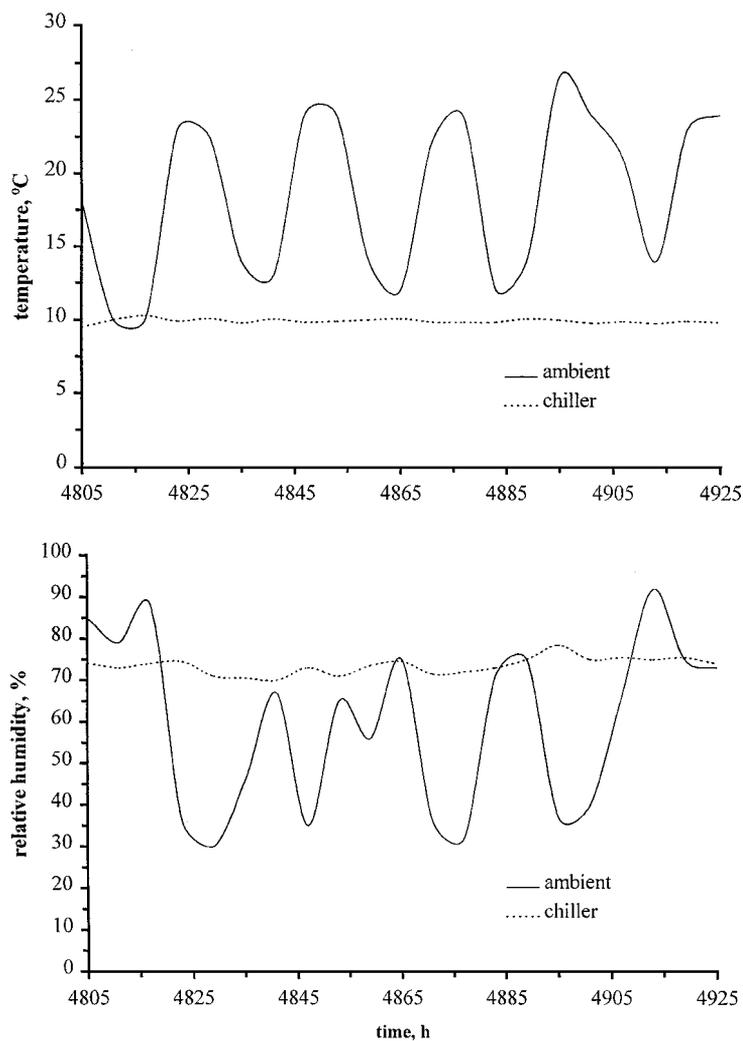


Figure 1.37. Temperature and relative humidity of ambient air and of air chilled by a commercial grain chiller under typical midwestern U.S. conditions. (Source: sales brochure, Zanotti, Suzzara, Italy.)

Table 1.25 contains the technical specifications of a typical commercial grain chiller.

The chilling rate of rice in a silo is shown in Fig. 1.38; note the slight change in the moisture content of the rice.

Aeration

Grain stored in bulk at an initially low uniform moisture content will over time increase in moisture content at some locations in the bin. This phenomenon is caused

Table 1.25. Specifications of a typical commercial grain chiller

Characteristic	Specification
Chilling Capacity (ton/d)	
Maximum	132
In summer	59–64
In autumn	100–109
Average	77–91
Flowrate of chilled air (m ³ /min)	
At static counter-pressure of:	
~1.0 kPa	85
~2.0 kPa	74
~3.0 kPa	59
Compressor cooling capacity (kW) ^a	33
Connected load	
Compressor	7.9
Cold-air fan	5.5
Condenser fan	0.55
At nominal cooling capacity	13.0
At start-up (38 A)	
With heating element	23.1
Without heating element	17.1
Power to control box, A	63.0

Source: [10].

^a At condenser temperature of 30°C and evaporator temperature of 0°C.

by a low rate of airflow occurring in the bin, resulting from a temperature difference between the grain near the bin walls and the ambient air surrounding the bin. The so-called natural-convection airflow currents lead to condensation and crusting of the grain, usually in the 0.3- to 0.5-m thick grain layer in the top-center of the bin. The detrimental effects of natural convection can be counteracted by minimizing the previously mentioned temperature difference between grain and air. This is the objective of the process of *aeration*, the intermittent moving of ambient air at low flow rate through stored grain.

The recommended airflow rate for aeration of silos in temperate climates is in the range of 0.025 to 0.10 m³min⁻¹ton⁻¹; in tropical regions higher airflows are employed, such as 0.05 to 0.25 m³min⁻¹ton⁻¹ (see Table 1.26). The time for the cooling front to

Table 1.26. Recommended airflow rate for aeration of grain stored at 13% to 15% moisture content (w.b.) (in m³min⁻¹ton⁻¹)

Storage Type	Temperate Climate	Subtropical Climate
Vertical	0.025–0.05	0.05–0.15
Horizontal	0.05–0.10	0.15–0.25

Source: [4].

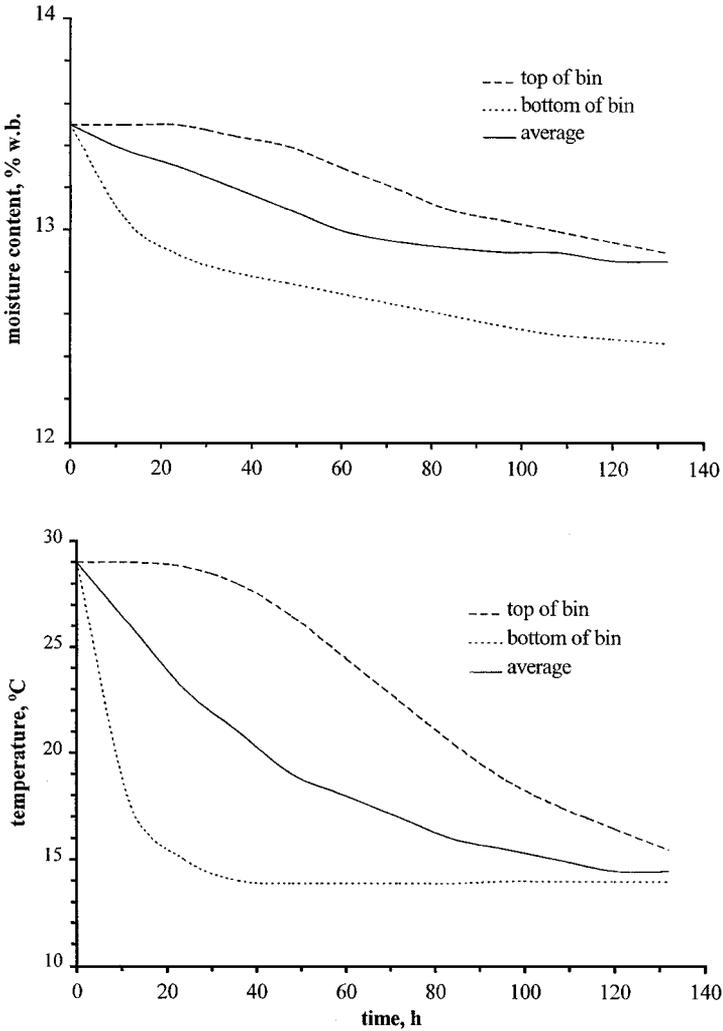


Figure 1.38. Temperature and moisture content of rice aerated with a grain chiller [11].

pass through a bin, and thus the time required for aerating a bin, depends on the airflow rate (and in temperate climates on the season) (see Table 1.27).

An aeration system consists of a fan, an air-supply duct, aeration ducts located in the bin (or a perforated floor), and an aeration controller. The specifications of the fan and air-supply duct are calculated using the airflow information in Section 1.3.1 of this chapter. Several potential air-distribution patterns in horizontal and vertical bins are shown in Fig. 1.39.

An aeration system should be automatically controlled because manual control of the fans is labor-intensive and inaccurate. Sophisticated controllers are computer-based and

Table 1.27. Approximate fan time for aeration of grain to equalize grain temperatures

Season	Airflow of 0.05 $\text{m}^3\text{min}^{-1}\text{ton}^{-1}$	Airflow of 0.25 $\text{m}^3\text{min}^{-1}\text{ton}^{-1}$
Fall	300	60
Winter	400	80
Spring	240	48

Source: [4].

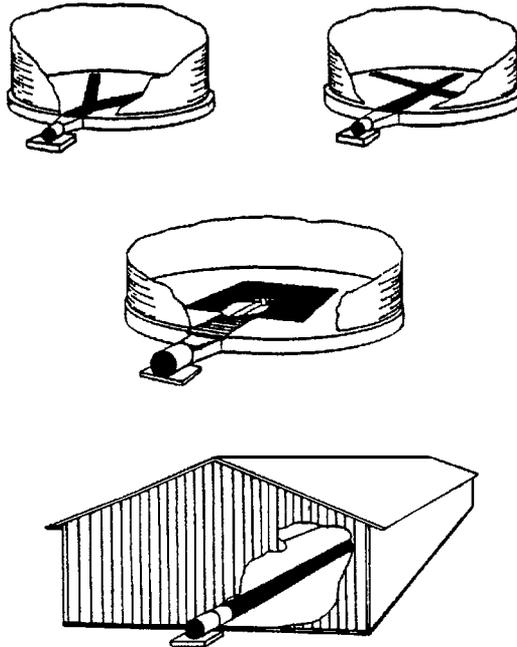


Figure 1.39. Typical grain aeration systems [4].

measure the temperature and relative humidity of the ambient air and of the interstitial air among the kernels in the bin [12]. Less sophisticated controllers base their fan-operating decisions solely on the air and grain temperatures, or only on the relative humidity of the ambient air. The reader is referred to Ref. [13] for specific information on commercial aeration controllers and to Section 1.3.3.

1.4.4 Grain Pests

Stored grain is subjected to the deleterious effects of grain pests, in particular to molds, insects, and rodents. The degree of pest activity is a function of the moisture content and temperature of the grain, the damage level of the grain, the foreign-material content of the grain, the type and hybrid of the grain, and the interstitial atmosphere around

the grain. In general, the lower the moisture content, the temperature, the damage level, and the foreign-material content of the grain, the longer it can be stored without being affected by one of the grain pests. Also, covered seeds (e.g., oats) store better than naked seeds (e.g., wheat).

Molds

Many mold species can develop on grains, in the field as well as in storage. Among the major field molds are species of the genera *Fusarium* and *Aspergillus*. Field molds can develop under high relative-humidity conditions (>88%), over a wide range of temperatures (10–35°C). If grain is properly dried, field molds do not further develop in storage.

Species of *Aspergillus* and *Penicillium* are among the principal storage molds of grains; each requires a minimum moisture content for growth (see Table 1.28). Likewise, development of a species is limited to a certain temperature range (see Table 1.29). The general effect of temperature and moisture content on the allowable storage time of maize is illustrated in Fig. 1.40.

The major losses caused by fungal growth in grains are decreases in germinability, discoloration of the seed germ, heating and development of mustiness, biochemical changes, potential production of toxins, and loss in dry matter. Of particular importance is the potential production of toxins.

Several grain molds produce toxins, called *mycotoxins*. They are defined as “fungal metabolites which when ingested, inhaled or absorbed through the skin cause lowered

Table 1.28. Conditions for growth of common storage molds on cereals at 25°C to 27°C

	Relative Humidity (%)	Moisture Content (% w.b.)
<i>Aspergillus halophilus</i>	68	12–14
<i>A. restrictus</i>	70	13–15
<i>A. glaucus</i>	73	13–15
<i>A. candidus</i> , <i>A. ochraceus</i>	80	14–16
<i>A. flavus</i> , <i>parasiticus</i>	82	15–18
<i>Penicillium</i> spp.	80–90	15–18

Source: [14].

Table 1.29. Conditions for growth of four toxin-producing molds

	Temperature Range (°C)	Relative-Humidity Range (%)
<i>Aspergillus flavus</i>	10–40	80–82
<i>A. parasiticus</i>	10–40	80–82
<i>A. ochraceus</i>	8–35	79–81
<i>Penicillium verrucosum</i>	0–35	80–84

Sources: [15, 16].

Table 1.30. Maximum mycotoxin levels in feed grains in the United States in 1998

Animal	Aflatoxin (ppb)	DON (ppm)	Zearalenone (ppm)
Nursery pigs	—	0.5	0.5
Young chicks and grow pigs	20	1.0	2.0
Finishing pigs	200	1.0	2.0
Breeding cattle and mature poultry	100	—	—
Finishing beef cattle	300	—	—

Source: [19].

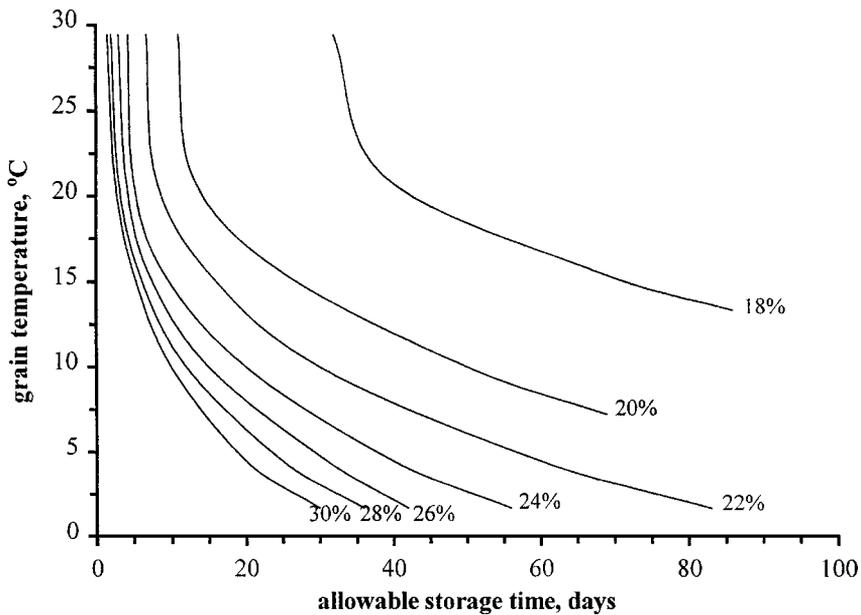


Figure 1.40. Allowable storage time for maize as a function of moisture content and temperature, based on limiting the development of storage molds or the equivalent of 0.5% dry-matter loss (17).

performance, sickness or death in man, or animals” [18]. Major mycotoxins are aflatoxins, vomitoxins (DON), and zearalenone. Table 1.30 lists the maximum allowable mycotoxin levels in feed in the United States in 1998.

Insects

Insects can cause major losses in stored grain, not only in tropical and subtropical regions but also in temperate climates. Hundreds of insect species have been found in grain storages. Table 1.31 lists some common grain-storage insects and their optimal growth conditions.

Table 1.31. Optimal development conditions of some common insect species found in grain storages

	Temperature (°C)	Relative Humidity (%)
<i>Sitophilus oryzae</i> (rice weevil)	26–31	70
<i>S. zeamais</i> (maize weevil)	27–31	70
<i>Rhyzopertha dominica</i> (lesser grain borer)	32–34	50–60
<i>Prostephanus truncatus</i> (larger grain borer)	25–32	80
<i>Sitotroga cerealella</i> (Angoumois grain moth)	26–30	75
<i>Plodia interpunctella</i> (Indian meal moth)	26–29	70
<i>Tribolium castaneum</i> (red flour beetle)	32–35	70–75
<i>Cryptolestes ferrugineus</i> (rusty flour beetle)	33	70–80
<i>Oryzaephilus surinamensis</i> (sawtoothed grain beetle)	31–34	90
<i>Trogoderma granarium</i> (khapra beetle)	33–37	25

Sources: [20, 21].

Losses inflicted by insects to stored grain consist of disappearance of a large portion of the kernels, damage to the germs, heating (followed by molding) of the grain, and contamination of the grain mass. The development of insects in grain storages can be prevented by controlling the temperature and moisture content of the grain or by modifying the interstitial air. In chilled grain storages, the grain temperature and equilibrium moisture content are kept low; in CA storages the oxygen content is maintained at a low level.

Stored-grain insects are divided into internal feeders and external feeders. The internal feeders develop from egg to larva to insect *within* grain kernels. The external feeders hatch from eggs laid on the *surface* of grain kernels. Internal feeders are the more destructive insects; major species are the rice and maize weevils, the lesser and larger grain borers, and the Angoumois grain moth. Among the common destructive external feeders are the Indian meal moth, the red flour and rusty grain beetles, and the sawtoothed grain beetle. Which insect species occur in a region depends on the local temperature and humidity conditions, and on the type of grain in storage. Thus, the khapra beetle (an external feeder) is a major pest in the tropics but is not found in the United States.

The infestation of stored grain by insects is limited by taking the following steps [4]:

- Remove all grain debris from in and around the bin before the harvest season.
- Treat the bin walls with a proper chemical at least 2 weeks before the bin is to be filled.
- Use a grain cleaner.
- Store grain at the proper moisture content.

- Cool stored grain by aeration or chilling to below 10°C (if possible).
- Monitor the grain temperature and moisture content and the presence of mold and insects.
- Aerate grain if the maximum grain temperature exceeds by 6°C the average 24-hour ambient temperature.
- Clean and sell or fumigate grain immediately after insects are discovered.

Fumigation (i.e., chemical treatment) of stored grain should be implemented by professional fumigators [22]. Only a limited number of chemicals still are available commercially (e.g., in 1998 in the United States only phosphine).

Rodents

Rodents are considered a storage pest because they consume and damage grains in the field and in storage, destroy baggage and storage structures, and transmit diseases that are dangerous to humans (i.e., through urine and droppings mixed with grain). Cleanliness during grain harvest and handling reduces the risk of rodents.

Three common rodents found throughout the world are the house mouse (*Mus musculus*), the brown rat (*Rattus norvegicus*), and the ship rat (*Rattus rattus*).

Two forms of rodent control are practiced. Poisons are used only if a rapid reduction in rodent population is required. Trapping is implemented if poisons are too dangerous and rodent odors must be avoided. The snap trap (i.e., mouse trap) and the steel animal trap are commonly employed.

Rodent-proofing of a storage facility is necessary to curtail the development of rodents. The following is recommended for rodent-proofing a storage facility:

- Exterior structures should be constructed of gnaw-proof materials.
- Openings should be closed or protected with doors, screens, or grates.
- Dead space within the interior of the storage structure should be avoided.

References

1. Hall, C. W. 1957. *Drying Farm Crops*. Ann Arbor, MI: Edward Brothers.
2. Lee, K. T., T. Y. Tan, and A. M. Seet. 1977. *Investigations into the Problems Involved in Storing Bulk Quantities of Milled Rice in Bag Stores: Report 1976*. Valencia, Spain: Institute of Agriculture and Food Technology.
3. Boumans, G. 1985. *Grain Handling and Storage*. New York: Elsevier.
4. Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1992. *Drying and Storage of Grains and Oilseeds*. New York: Van Nostrand Reinhold.
5. Busta, F. F., L. B. Smith, and C. M. Christensen. 1980. Microbiology of controlled atmosphere storage of grains. In *Controlled Atmosphere Storage of Grains*, ed. J. Shejbal. New York: Elsevier.
6. Muda, A. R. 1988. Sealed storage of milled rice under carbon dioxide. In *Bulk Handling and Storage of Grain in the Humid Tropics*, eds. B. R. Champ, and E. Highley. Canberra, Australia: ACIAR.
7. Bell, C. H., and D. M. Armitage. Alternative storage practices. In *Storage of Cereal Grains and Their Products*, 4th ed., ed. D. B. Sauer. St. Paul, MN: AACC.

8. Shejbal, J. 1979. Storage of cereal grains in nitrogen atmosphere. *Cereal Foods World* 24(3):192–194.
9. Banks, H. J., and A. K. Sharp. 1979. Insect control in a small stack of bagged grain in a plastic enclosure. *Australian Journal of Animal Husbandry* 19(2):102–107.
10. Sulzer USA, Inc. 1993. *Grain Chilling*. Lindau, Germany: Sulzer-Escher-Wyss.
11. Maier, D. E. 1992. The chilled aeration and storage of cereal grains. Ph.D. diss., Michigan State University, East Lansing, MI.
12. Moriera, R. G., and F. W. Bakker-Arkema. 1992. Grain dryer controls. *Cereal Chemistry* 69:390–396.
13. Driscoll, R. 1996. In-store drying and grain psychrometrics. In *Grain Drying in Asia*, eds. B. R. Champ, E. Highley, and G. I. Johnson. Canberra, Australia: ACIAR.
14. Christensen, C. M., and H. H. Kaufman. 1969. *Grain Storage: The Role of Fungi in Quality Loss*. Minneapolis, MN: University of Minnesota Press.
15. Christensen, C. M., and R. A. Meronuck. 1986. *Quality Maintenance in Stored Grains and Seeds*. Minneapolis, MN: University of Minnesota Press.
16. Pitt, J. I. 1995. Under what conditions are mycotoxins produced? *Australian Mycotoxin Newsletter* 6(2):1–2.
17. Steele, J. L. 1967. Deterioration of damage shelled corn as measured by carbon dioxide production. Ph.D. diss., Iowa State University, Ames, IA.
18. Pitt, J. I. 1996. What are mycotoxins? *Australian Mycotoxin Newsletter* 7(4):1–2.
19. United States Department of Agriculture. 1997. *Maximum Mycotoxin Levels in US Feeds*. Washington, DC.
20. Pedersen, J. R. 1992. Insects: Identification, damage and detection. In *Storage of Cereal Grains and Their Products*, ed. D. B. Sauer. St. Paul, MN: AACC.
21. Champ, B. R. 1985. Occurrence of resistance to pesticides in grain storage pests. In *Pesticides and Humid Tropical Grain Storage Systems*, eds. B. R. Champ, and E. Highley. Canberra, Australia: ACIAR.
22. GASGA. 1996. Risks and consequences of the misuse of pesticides in the treatment of stored products. Technical Bulletin No. 2. Wageningen, the Netherlands: CTA.

1.5 Grain Drying and Storage in the Tropics

Juarez de Sousa e Silva and Pedro Amorim Berbert

Although cereal grains and oilseeds can be produced throughout the year in tropical regions, productions are normally seasonal and harvest takes place at certain times of the year. Because of this fact, it is necessary to store grains for different lengths of time in order to provide consumers with an uniform grain supply.

With some exceptions, including parts of Brazil, Australia, and Argentina, grains such as beans, corn, and rice historically have been produced by farmers owning small land areas (less than 50 ha) and generally are associated with concepts of low production and yield, low capital investment, and low level of technology use. Value-added grains and oilseeds generally are produced with high levels of technology use. Commercialization and distribution of their products generally are made through well-organized cooperative

systems. These farmers have easy access to information on stock-market prices, quality standards, and up-to-date technologies.

It is not difficult to realize how important is the need for grain preservation in the tropics. However, providing a storage technology capable of preserving the quality of cereal grains in various regions in the tropics is a very complex undertaking. To successfully store grains in the tropics, it is necessary to understand how the product deteriorates and the methods generally used to control the deterioration process. Much of the tropical region is characterized by climates that makes it unsafe to store grains. High temperatures and relative humidities predominate over prolonged periods of time, thus increasing the potential for deterioration due to insects, birds, molds, and rodents. Even in the best-constructed and best-managed facilities, storing grain in the tropics is a very difficult task.

Despite the availability of various types of storage facilities, which vary from discarded oil drums to modern silos, the ways in which grains are harvested, handled, dried, and stored in developed regions of the tropics do not differ from those used either in the United States or in Europe. However, high initial moisture contents at harvest and warm weather throughout the year, which prompts an intense level of biological activity (grain respiration, insect and mold development), require from managers of stored product facilities in the tropics frequent supervision of the stored grain and a more careful approach to quality aspects as compared with those facilities located in regions of temperate climates.

1.5.1 Deterioration During Storage

The main objective of storing grain in a proper way is to maintain, throughout the whole storage period, the biological, chemical, and physical characteristics that the grain possessed immediately after harvest. One of the most critical physiological factors that determines a successful grain-storage process in the tropics is its moisture content. A high moisture content leads to storage problems because it creates a favorable condition for mold and insect growth, an increased grain respiration rate, and germination during storage. One of the products of respiration is heat, and reduction of temperature of the harvested crop can help reduce the rate of respiration and thus increase the storage life of the product. Also, lowering the temperature reduces insect and mold activities, and consequently the rate of spoilage is reduced. Intense insect and mold growth are recognized as the major problems preventing successful grain storage in the tropics.

1.5.2 Drying Systems

Low-temperature and Sun Drying

Low-temperature drying is a process used to dry cereal grains that uses ambient or slightly heated air and employs bins normally used for grain storage. Thus, the process is normally referred to as *in-bin drying*. The drying bin must have some special characteristics—perforated floor (10% to 25% of area perforated), uniform distribution of the drying air—and fan selection must be based on grain initial moisture content, bin size, and allowable drying time. Electric resistance heaters or gas, wood, and oil-burning furnaces are the most common heat sources.

Table 1.32. Conditions for low-temperature drying (25°C and 65% relative humidity) of selected products in the tropics

	Maximum Initial Moisture Content (% w.b.)	Minimum Airflow Rate (m ³ /m ³ ·min)
Beans	18	3.0
Corn	18	3.0
Rice	18	3.0
Parchment coffee	22	5.0

Heating the air some degrees above ambient temperature may bring some mold-related problems if the bin is rapidly filled. Table 1.32 shows the mean airflow rate used for some tropical products at different moisture contents and for mean ambient conditions. It is recommended that the drying bin be filled in no fewer than 5 days.

To avoid deterioration and to reduce fan power requirements, it is recommended that a new layer of wet grain be added to the bin only after the previous layer already is dried to the desired moisture content. While designing a low-temperature drying system, the engineer must remember that the daily moisture-content reduction of the crop in the field is roughly 0.5%. Monitoring a low-temperature drying system requires daily verification of relevant ambient temperature and relative humidity and grain temperature and moisture-content conditions. In the case of using slightly heated air, at the end of the drying the grain must be cooled at ambient temperature.

Figures 1.41 and 1.42 show types of solar dryers used for coffee drying [1]. The number of drying panels needed to dry a determined volume of coffee may be calculated as follows:

$$N_p = 13N_d - (8N_d/3), \tag{1.9}$$

where N_p is the total number of panels and N_d is the number of panels used daily. Sun drying on paved terraces or even on roads is a common procedure in remote areas of developing countries in situations in which no mechanical drying systems are available

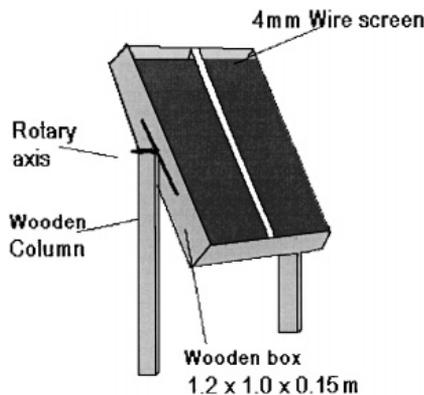


Figure 1.41. Solar coffee dryer.

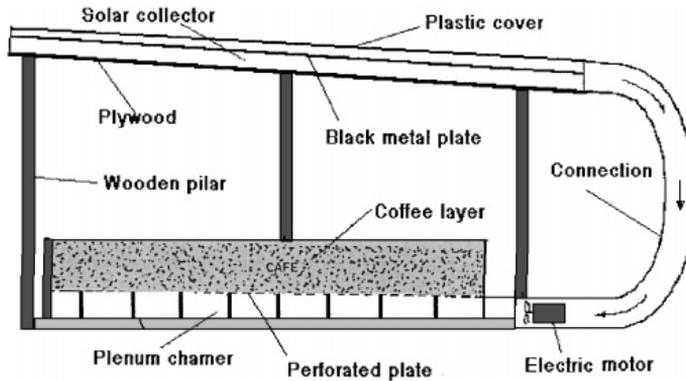


Figure 1.42. Fixed-bed solar dryer.

or there is a lack of appropriate space to dry unexpected production due to high yields. Sun drying on a drying terrace or floor is a procedure that requires high labor inputs per ton; mechanized continuous-flow high-temperature dryers with handling equipment require very little labor. As a result of this, sun drying only fits the situation in which labor is cheap and supply is abundant during the harvest season. According to Teter [2], this still is the prevailing situation in many developing countries, especially at village level. Products dried in this way include beans (*Phaseolus vulgaris* L.), rice (*Oryza sativa* L.) and coffee (*Coffea arabica* L.).

Another overwhelming reason for choosing sun-drying procedures on paved terraces or even on roads is related to economics: It is estimated that for some products sun drying may be half the cost of mechanical drying [2]. It is widely recognized that sun drying of rice results in more broken kernels because it is difficult to control the temperature of the product. In most situations in which the farmer applies the sun-drying procedure using terraces or roads, the temperature of the product often exceeds the allowable maximum value (approximately 40°C), and rewetting of the dried product, mainly rice, causes fissuring of the endosperm.

Sun drying on roads is not a recommended procedure because it generally results in a product of poor quality as compared with a well-conducted artificial drying. Besides, the use of roads to dry agricultural commodities is prohibited in most countries.

High-temperature Drying

Among the grain-drying systems used in the tropics, the high-temperature, high-capacity drying method is the most widely used because, in general, it is independent of weather. In choosing between the high- and low-temperature drying methods, a careful economic balance must be calculated. Unfavorable weather may add to the cost of low-temperature and sun drying and also impair the quality of the grain by creating favorable conditions for the growth of molds.

Airflow rates normally employed in high-temperature drying systems in the tropics depend on dryer type but are generally greater than 10 m³/min-ton. With slight design modifications, high-temperature dryers used in the tropics are very similar to those used in the United States and Europe. Of the wide variety of dryers available on the market,

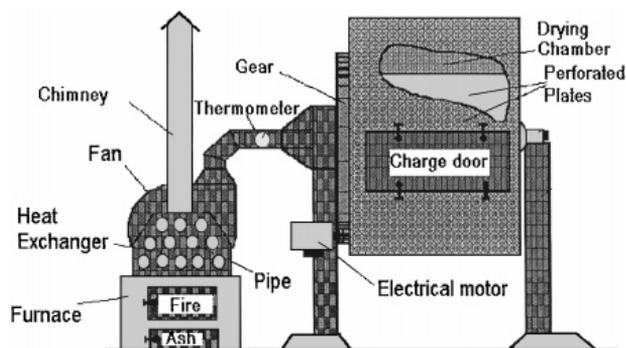


Figure 1.43. Rotary dryer.

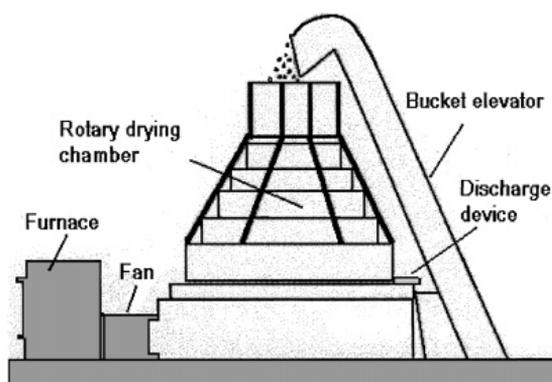


Figure 1.44. Rotary dryer.

rotary dryers (Figs. 1.43 and 1.44), column-type dryers, and mixed-flow dryers are the most popular, with nominal capacities varying in the range from 0.5 to 100 ton/h.

Fixed-bed Dryers

A fixed-bed dryer is a modified version of a batch-in-bin dryer, and it usually is constructed using materials easily found in the farm and applying low levels of technology input. The drying air may be heated by a directly or indirectly fired furnace that uses wood, coal, or biomass as fuel. Figure 1.45 shows a type of fixed-bed dryer developed by Silva and Lacerda Filho [3], and Table 1.33 gives its operational characteristics.

Owing to its design, the fixed-bed dryer presented in Fig. 1.45 may be used to dry a wide variety of agricultural products, including those that do not flow easily in handling equipment and mechanical dryers: high moisture-content coffee cherries, beans in pods, cocoa beans, hay, chopped grass, corn on the cob, and cassava.

Natural-Convection Dryer

The natural-convection dryer presented in Fig. 1.46 is another type of dryer used by small-scale grain producers. Like the fixed-bed dryer, it may be used to dry a variety of agricultural products, including those with flow problems. The air is heated using a heat

Table 1.33. Operational characteristics of the fixed-bed dryer developed by Silva and Lacerda Filho

Product	Drying-air Temperature (°C)	Layer Depth (m)	Stirring Interval (h)
Corn	60	0.4	2.0
Beans	40	0.4	2.0
Rice	45	0.3	1.5
Soybeans	45	0.6	2.0
Coffee (50%–60% w.b.)	50	0.5	3.0
Coffee (30%–35% w.b.)	50	0.4	3.0
Cassava	40	0.3	3.0

Source: [3].

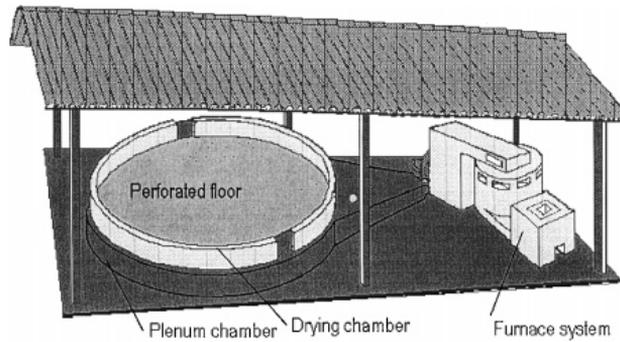


Figure 1.45. Fixed-bed drying.

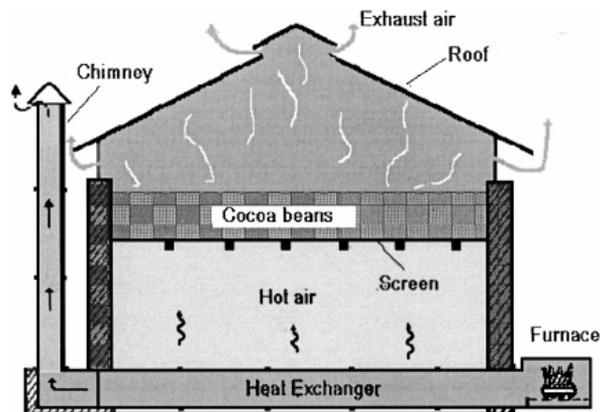


Figure 1.46. Natural-convection dryer.

exchanger located inside the dryer. Despite its simplicity and low-construction cost, this type of dryer is suitable for regions in which electric energy is not yet available. The air is forced up through the product due to a pressure gradient created by a temperature difference between the drying air and ambient air.

Despite the advantages brought about by the requirement of no moving parts, including a fan, and its low cost, this type of dryer generally is criticized for its low drying efficiency. Also, the airflow rate and the drying-air temperature are difficult to control during the drying process, and the final moisture-content difference is generally higher than normally accepted. If the heat exchanger is damaged, some leaking of smoke generally occurs, which could worsen the quality of the dried product.

1.5.3 Cacao-Bean Drying

Freshly harvested cacao seeds are submitted to a series of unit operations before they are ready for processing into cocoa powder. These freshly harvested cacao seeds are covered with a slippery layer of mucilage of variable thickness. The mucilage is insoluble in water, and it adheres to the cacao seed too firmly to be dispersed and removed by washing. This mucilage has to be removed to prevent quality deterioration during drying. The most common method of removing the mucilage is natural fermentation. The cacao seeds are placed in wooden tanks and the natural enzymes present in the mucilage itself complete the digestion. The seeds are allowed to remain in the fermentation tanks for 6 or 7 days. After this period, the mucilage has become completely dispersible and may be washed away. Then, the seeds with moisture contents ranging from 55% to 65% (w.b.) are transferred to a dryer in which their moisture content is reduced to 8% (w.b.). The process of flavor and taste development starts during the fermentation process and continues up to the end of the drying process. These are the most important operations in preparing good-quality commercial cocoa.

In order to produce a high-quality product, cacao seeds must be dried slowly and uniformly by using drying temperatures not higher than 60°C. As for coffee, it is essential that cacao seeds present a highly uniform moisture-content distribution at the end of the drying. Heat and mechanical damage must be avoided whenever possible. Mold development in the seed coat is not considered a serious problem, for these coats are removed during processing. However, if the seed is damaged and the cotyledons are invaded by fungi, there certainly will occur quality deterioration during chocolate-flavor and taste development.

Contamination with smoke leaking from the heat-exchanger unit located in the furnace is one of the major causes of quality deterioration. It is even advisable that no smoke-producing units but the one used in the dryer be located close to the drying and storage facilities. As a matter of fact, all types of high-temperature dryers will produce some smoke-related problems because small leaks in the heat exchanger are difficult to locate and fix.

Although losing ground to the high-temperature drying systems, the sun-drying technique still is adopted in some regions to dry cacao seeds. The mechanisms of heat and mass transfer during the solar drying of cacao seeds do not differ from those observed

Table 1.34. Capacities of platform solar dryers

Dimensions (width × length, m)	Capacity (ton/y)
3.0 × 6.0	4.0
4.0 × 8.0	7.0
5.0 × 10.0	12.5

Source: [1].

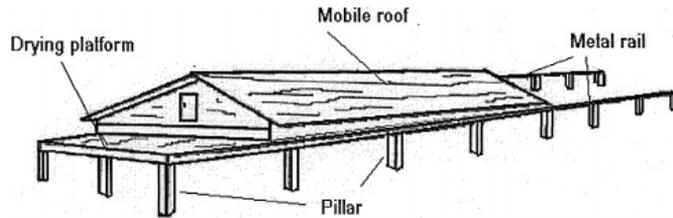


Figure 1.47. Platform solar dryer.

in other crops such as coffee. In Brazil, a very expensive type of solar dryer called a *platform dryer* is widely used (Fig. 1.47). It consists of a platform covered with a movable roof under which the seeds are placed to dry. If sunshine is available, the platform is uncovered and the seeds are allowed to dry. During the night and rainy days, the roof is used to cover the platform and hence to protect the seeds. Loading and unloading are done by hand, and the cacao seeds also are stirred by hand during drying. Table 1.34 summarizes the dimensions most commonly used in the construction of this type of dryer and their nominal capacity.

In the vast majority of cacao-producing areas, the harvest period coincides with the rainy season and days of low solar radiation. As a consequence, the use of sun-drying techniques, including the platform dryer, is not a good option. To keep up with the harvest rate, farmers must use high-temperature dryers, and these include cross-flow, fixed-bed, rotary, and convection dryers.

1.5.4 Physical Properties of Cacao Seeds

Thermal Conductivity

The equations presented in Table 1.35 relate the thermal conductivity, K ($\text{kW}\cdot\text{m}^{-1}\text{K}^{-1}$), of cacao seeds with moisture content, $0.05 \text{ d.b.} \leq M \leq 1.07 \text{ d.b.}$, for three levels of drying air temperature, 60, 70, and 80°C [4].

Specific Heat

The following equation ($r^2 = 0.78$), developed by Sasseron [4], represents the specific heat at constant pressure, c_p ($\text{kJ}\cdot\text{kg}^{-1}\text{K}^{-1}$), of cacao seeds as a function of moisture content, $0.05 \text{ d.b.} \leq M \leq 1.20 \text{ d.b.}$

$$c_p = 3.09 + 1.82M - 1.58M^2 \quad (1.10)$$

Table 1.35. Thermal conductivity of cacao seeds

Drying-air Temperature (°C)	Equation	r^2
60	$K = 0.1362 + 0.2554M$	0.96
70	$K = 0.1343 + 0.2561M$	0.97
80	$K = 0.1061 + 0.2878M$	0.98

Source: [4].

According to Eq. (1.10), for moisture contents in the range from approximately 0.43 to 1.20 d.b., the specific heat of cacao seeds decreases with increasing moisture. This fact clearly contradicts the expected physical behaviour and must be accounted for by experimental errors during measurements.

Bulk Density

The bulk density, ρ ($\text{kg}\cdot\text{m}^{-3}$), of cacao seeds as affected by moisture content, 0.05 d.b. $\leq M \leq 1.07$ d.b., may be represented by either of the following equations developed by Sasseron [4], with coefficients of correlation of 0.93 and 0.99, respectively:

$$\rho = 938.2 + 153.5M \quad (1.11)$$

$$\rho = 875.8 + 582.8M - 613.7M^2 + 233.0M^3 \quad (1.12)$$

Thermal Diffusivity

The effect of moisture content, 0.05 d.b. $\leq M \leq 1.07$ d.b., on the thermal diffusivity, α (m^2s^{-1}), of cacao seeds during drying at 70°C is given by the following equation [4], with a coefficient of determination of 0.97:

$$\alpha = 3.67 \times 10^{-5} + 7.70 \times 10^{-5}M \quad (1.13)$$

Thin-layer Drying Equation

The following equation ($r^2 = 0.99$) describes the drying rate of a thin-layer of cacao seeds for drying-air temperatures ranging between 60 and 80°C.

$$MR = 0.4329 \exp \left[- (0.5036 - 0.0141T_{abs} + 0.00013T_{abs}^2) t \right] \\ + 0.5670 \exp \left[- (-23.9335 + 0.6973T_{abs} - 0.0046T_{abs}^2) t \right], \quad (1.14)$$

where T_{abs} is the absolute air temperature (K), and t is time to dry to MR (moisture ratio) with drying air temperature T_{abs} (h).

References

1. Silva, J. S., and P. C. Corrêa. 1995. Secagem com energia solar. [Solar drying]. In *Pré-processamento de produtos agrícolas [Handling, Drying, and Storage of Agricultural Products]*, ed. J. S. Silva, pp. 145–161. Juiz de Fora, MG, Brazil: Departamento Editorial do Instituto Maria.
2. Teter, N. 1987. Paddy drying manual. FAO Agricultural Services Bulletin no. 70. Rome: Food and Agriculture Organization of the United Nations.

3. Silva, J. S., and A. F. Lacerda Filho, 1984. Construção de secador para produtos agrícolas [Design and construction of a fixed bed dryer for agricultural products]. Informe técnico no. 41. Viçosa, MG, Brazil: Conselho de Extensão da Universidade Federal de Viçosa.
4. Sasseron, J. L. 1984. Avaliação de propriedades físicas e curvas de secagem, em camadas finas, de amêndoas de cacau (*Theobroma cacao* L.) [Determination of some physical properties and a thin-layer drying equation of cacao (*Theobroma cacao* L.) seeds]. M.Sc. thesis, Universidade Federal de Viçosa, MG, Brazil.

2 Root Crops

J. De Baerdemaeker, Co-Editor

2.1 Root Crop Quality and Losses

J. De Baerdemaeker, N. Scheerlinck, P. Jancsó, and P. Verboven

Storage of root crops reduces the seasonal character of crop availability for the fresh market or for the food industry. Most products are harvested during a specific season that may last several months, but the consumption of these staple foods can occur all year round. For example, in the Northern Hemisphere, potatoes are harvested between May and October, but by using appropriate storage practices a quality product is available for the consumer throughout the year.

Similarly, the storage of a crop has economic advantages, as it extends the processing season and keeps the processing plants running continuously. It also helps food processors bridge short-term periods of low supply of freshly harvested products. Sometimes the availability of good storage facilities can reduce the purchase cost, as raw materials can be purchased at favorable market prices. For the farmers, crop storage may lead to a better average price by avoiding an oversupply on the market during the harvesting season.

It should be noted that storage conditions are important not only while the crop is being stored but also during transportation.

A Committee on Postharvest Food Losses in Developing Countries of the U.S. National Academy of Sciences–National Research Council issued a report in 1978 with estimates of food losses. The overall losses for roots and tubers vary between 5% and 100%. The main causes of product loss are mechanical injury, physiological losses, and losses due to diseases. Attacks on stored products by rodents or insects may be important in some cases but are mostly of minor importance in comparison with damage resulting from microorganisms. One can assume that similar causes of loss exist in most countries, but that the extent of loss may vary depending on the conditions and technical expertise available for storage design and management.

In the following pages a general discussion will be given on quality aspects and product properties for root crops and how they are affected by growing conditions. Causes of losses and some influencing factors also are given. In the last subsection of this section, a general approach to crop storage modeling is given in an effort to combine experimental evidence and physical phenomena in order to gain insight in storage behavior of crops. Other sections deal with a number of specific root crops. From an understanding of the

basic interrelationships between crop properties and crop physiology, the causes of crop deterioration and damage, and the physical aspects of storage can often lead to simple changes in storage practices that are effective in reducing losses.

2.1.1 Morphology of Roots, Tubers, and Bulbs

A morphological classification of plant parts allows an understanding of the nature of the harvested product. When taking into account the development stage of the plant or the plant part, it can help to predict the storage behavior and the handling requirements, even if no specific product information is available. An illustration of the plant parts used as vegetables is given in Fig. 2.1 [1]. Roots, tubers, and bulbs are the belowground structures of interest in this section. These parts serve as storage organs, containing

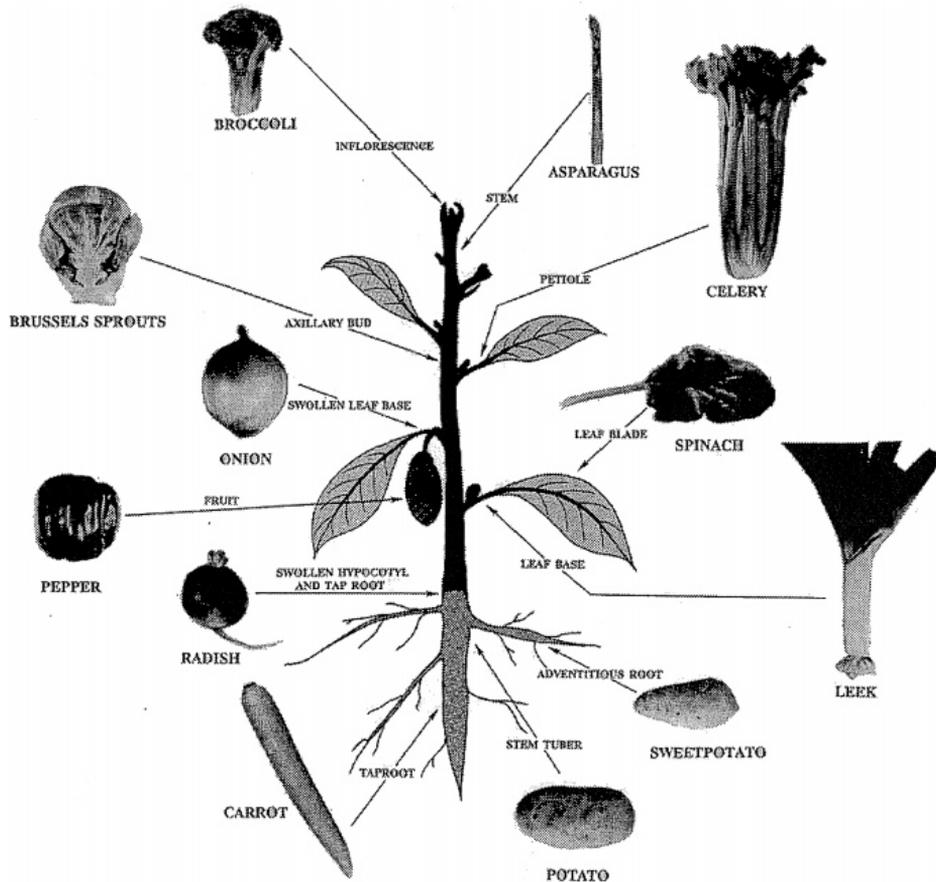


Figure 2.1. Plant parts utilized as food are derived from virtually every portion of the plant. This diagram illustrates examples of various parts from a cross-section of plants used as vegetables.

(Source: [2])

products accumulated during photosynthesis. The fleshy roots, tubers, or bulbs often are the only vegetative organs of a plant that are capable of surviving severe environmental stresses such as prolonged periods of cold or drought. They can be used as sources of raw material for human consumption or for processing. During a dormant period, for example after harvest, the buds of the storage organs use the stored reserves to maintain a low metabolic activity.

Roots

The storage organs of several crops are modified roots that contain mainly starch and sugar reserves. In carrots, the storage root is formed from the hypocotyl and taproot tissue. Secondary growth results in a central xylem core surrounded by phloem and pericycle tissue with a massive development of parenchyma cells containing starch and sugars.

The sweet potato is an adventitious root with an anomalous secondary growth. The fleshiness is due to a large volume of parenchyma in the primary and secondary xylem. During the secondary growth, the epidermis is replaced by protective tissue called the *periderm*.

Tubers

Tubers, for example potatoes, are underground parts that are anatomically the tip of a stem or rhizome with the appearance of a root. They have visible leaf and branch buds and are characterized by a central vascular cylinder and a thick cortex. The phloem is larger than the xylem. The rapid volume expansion of potato tubers is due to the proliferation of parenchyma around the pith. The stored reserves are mostly starch with some sugars and proteins.

Bulbs

Bulbs, such as onions, are underground buds in which the stem is reduced to a late with very short internodes, and the sheathing leaf bases are swollen to form a storage organ. At normal harvest maturity, the aboveground parts of the leaves shrivel, while the swollen leaf bases remain alive.

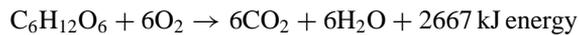
Adequate curing or drying of the neck and the outer leaf bases forms a protective coating of dry tissue. During the dormant period, the metabolic activity of these storage organs is low, and their keeping quality is good. The protective periderm originates from layers of tightly arranged cork cells with virtually no space between cells. When mature, these cells are suberized and contain layers of suberin, a fatty acid, and wax in the cell walls. The tissue of potato tubers or of sweet-potato roots maintains its ability to form periderm even after harvest, provided that favorable temperature and humidity conditions exist. Warmth and a high relative humidity during a period of a few days after harvest favors the formation of periderm and of wound periderm, periderm formed when crops are damaged during harvest. The ability to heal damaged or cut periderm, by forming a new layer, protects the tissue from excessive water loss or invasion by pathogens.

2.1.2 Product Respiration

Respiration is a central process that occurs in all living cells; it is essential for the maintenance of life in products after harvest. The function of respiration is the release

of energy and the formation of carbon skeletons, and it is imperative for synthesis or maintenance reactions after harvest. The respiratory activity does not require light and occurs in the mitochondria and cytoplasm. The substrates used are oxygen and stored carbon compounds, such as starch. Carbon dioxide, water, and energy are the end products. Because these mostly are released into the surrounding atmosphere, the overall effect is a loss in weight of the stored product. The utilization of the stored energy is a process that has an effect on the product quality and is related to the overall metabolic changes that occur in the stored plant. Therefore, although certain metabolic changes may occur without a measurable change in respiration rate, the respiration rate remains a general indicator of the overall metabolic rate.

A simplified representation of the process is:



As there is little cell development or growth in stored products, the respiration energy is mainly in the form of heat rather than adenosine triphosphate.

The measurement of the respiration rate can be based on concentration changes in any of the reactants or products involved in the process. In general, oxygen utilization or carbon dioxide production is used, because these can be measured with relative ease and adequate accuracy. Techniques for measuring the respiration rate are not discussed here [1].

The respiratory activity of plants is strongly affected by a number of crop factors and environmental factors. Because the end quality of a stored product is a direct result of the respiration activity, it is mandatory to have a proper management and control of these factors in order to optimize storage life.

Crop Factors

Species and Cultivars

Although differences in respiration rate may be expected between species, there may also exist substantial differences among cultivars, resulting in differences in their storage potentials [1].

Moisture Content

In general, metabolic processes slow down with decreasing moisture content. However, decreasing the moisture content of fleshy products like roots or tubers is not an attractive method to control respiration, because moisture content is closely related to product quality.

Surface and Volume Properties

The respiration rate of a product is usually proportional to the product mass. However, gas exchange with the environment occurs at the product surface, and the surface-to-volume ratio can play an important role when considering the appropriate storage conditions. In addition, the gas-diffusion properties of both the fleshy tissue and the surface tissue are important. They may result in considerable gradients in gas concentrations between the fleshy tissue and the surrounding tissue [1]. Natural surfaces of the products like the epiderm or the dried outer layers of onions tend to increase the diffusive resistance to the migration of oxygen, carbon dioxide, or water. In a later section, these

diffusion resistances are incorporated in the mathematical models for describing storage processes.

Cultural Practices and Stage of Development at Time of Harvest

The product composition in general is affected by these factors and in turn may affect the respiratory behavior. This explains, in part, differences in final quality that exist among crops harvested at different locations but stored in the same storage room.

Wounding

The respiratory activity of wounded plant tissue increases because of an increase in the required healing substances such as lignin, suberin, or sometimes also callus. Infection of the wounds by microorganisms also increases the respiration because of defense reactions by the cells. In addition to these effects, wounding also alters the gas diffusion resistance of the product surface.

Environmental Factors

Temperature

The metabolic rate of a harvested product is strongly influenced by the product temperature. An increased temperature results in increased reaction rates; not all reactions have the same change in rate with temperature. The change in respiration rate due to a change in temperature represents the overall effect of temperature on the different chemical reactions of the respiration process. Keeping the product quality throughout a storage period as near as possible to the quality at harvest time requires that the metabolic processes be slowed down as much as possible. This is best achieved by storage at low temperature, provided that no other adverse effects, such as cell-membrane damage, occur at low temperatures.

Some metabolic processes are exceptions to this overall effect. For example, in potatoes the respiration rate decreases with temperature, but the formation of sugars increases dramatically with a decrease in temperature below 10°C.

Different equations have been proposed to express the temperature dependency of the respiration rate. One such measure is the Q_{10} value, the ratio of the respiration rate at one temperature (T_1) to the rate at a temperature 10°C higher [1]:

$$Q_{10} = \frac{\text{rate at } T_1 + 10^\circ\text{C}}{\text{rate at } T_1} \quad (2.1)$$

For many products the Q_{10} value for respiration is between 2.0 and 2.5 in the temperature range between 2°C and 25°C.

Another way to describe the temperature dependency of the respiration rate is using an Arrhenius-type equation.

This is of the form:

$$\text{Rate constant} = Be^{-\frac{A}{RT}} \quad (2.2)$$

With R the gas constant, T the absolute temperature, and A and B constants.

Based on data from the U.S. Department of Agriculture [2], the carbon dioxide production of products can be expressed as a function of temperature, by a least-square

Table 2.1. Coefficients for carbon dioxide production by commodities

	Skin Mass Transfer Coefficient k_s (g/m ² ·s·MPa)			Respiration Coefficients		
	Low	Mean	High	VPL	f	g
Carrots	31.8	156.0	361.0	0.99	0.05002	1.793
Onions	—	0.888	—	0.98	3.668×10^{-4}	2.538
Potatoes	—	0.635	—	0.98	0.01709	1.769
Sugar beets	9.09	33.6	87.3	0.96	8.591×10^{-3}	1.888

Source: [3].

regression fit of the form [3]:

$$\dot{m}_{\text{CO}_2} = f \left(\frac{9T_m}{5} + 32 \right)^g, \quad (2.3)$$

where \dot{m}_{CO_2} is the carbon dioxide production per unit mass of a product (mg kg⁻¹ h⁻¹), T_m is the mass average product temperature (°C), and f and g are respiration coefficients given in Table 2.1. The rate of heat generation by respiration, W_{resp} (J kg⁻¹ h⁻¹), is given by:

$$W_{\text{resp}} = 10.7\dot{m}_{\text{CO}_2} \quad (2.4)$$

It should be noted that even at low temperatures the product is still characterized by a low metabolic activity, and subsequently heat is still generated. This internal heat generation in the product causes the product temperature to be slightly higher than the storage-room air temperature. This may not have a large effect on the respiration activity, but it can greatly affect the vapor-pressure difference between the product and the surrounding air, thus influencing the moisture balance of the product.

Gas Composition

The gas composition of the atmosphere in which a root product is stored has a strong influence on the respiratory activities of the product. As this topic has been addressed in the chapter on fruit storage, only a few aspects are stressed here. Although fruits grow under conditions of low diffusive resistance in the surrounding air, roots or tubers normally grow under conditions of considerable diffusive resistance. There is a significant difference in gas composition and diffusivity between growing and storing conditions. This has an influence on the gas-exchange rate, and therefore on the metabolic activity of the tissue. An overview of the different resistances to gas exchange between product and ambient air is given in Fig. 2.2.

The respiratory activity of most stored root products decreases substantially if the external oxygen concentration drops below 10%. At very low oxygen concentrations, anaerobic metabolic processes start. For sweet potatoes, for example, this may already be the case between 5% and 7% oxygen [1]. Of course, the internal diffusion resistance and the rate of oxygen consumption are also controlling elements for the internal oxygen concentration. The physiological state of the product and the size of the cells and the

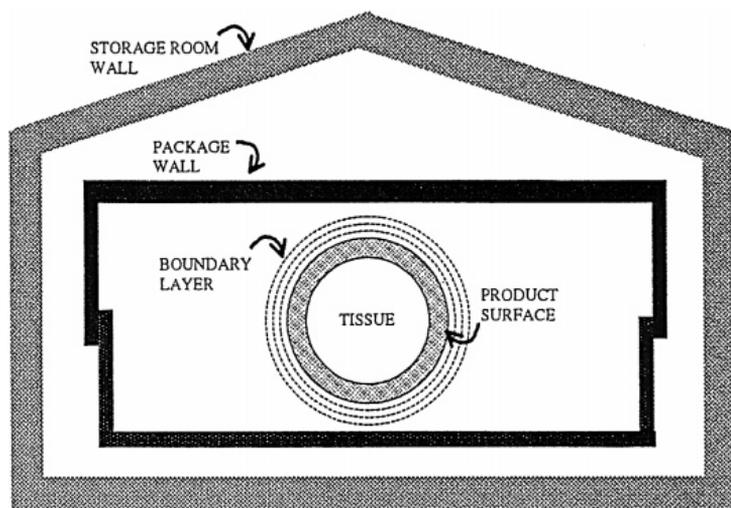


Figure 2.2. Resistances to gas exchange in a harvest product include storage walls, package wall, boundary layer, product surface, and tissue. The resistances of storage walls, package walls, and product surfaces are often manipulated for certain postharvest products to extend storage life.

(Source: [1])

internal pores in the various layers are important. This may explain differences in storage behavior among varieties and cultivars, and also among the individual products in a batch and among growing seasons.

An increased concentration of carbon dioxide in the ambient air has an effect on several biochemical processes, slowing down the overall respiratory activity. Again, this effect may not be the same in all tissues or at all carbon dioxide concentrations. Potato tubers, onions, and beet roots exhibit a marked increase in respiration activity at carbon dioxide levels between 30% and 70%, a phenomenon that does not occur under normal storage conditions.

Temporary exposure of the tissue to increased but commonly used carbon dioxide levels also slows down the respiration rate; this effect vanishes when the carbon dioxide concentration is reduced to normal values. Note that, similar to oxygen, the carbon dioxide level in the tissue is the result of the respiratory activity, the diffusion resistances, and the ambient concentrations.

Ethylene is a plant hormone that can significantly affect the respiratory activity of plant tissues. Because most stored products produce ethylene, accelerated respiratory activity ensues if this hormone is allowed to accumulate in the storage room [1].

Concentration and *concentration gradient* are commonly used terms. However, in describing the processes that govern the uptake or diffusion of gases, it is more appropriate to use the concepts of partial pressure and pressure gradient of the different components of a gas mixture or of a liquid in equilibrium with the gas. Then, the effect of possible differences in temperature can easily be accounted for. This can be important under

Table 2.2. Effect of temperature and oxygen concentration on the respiratory rate of various commodities

	Carbon Dioxide Production (mg·kg ⁻¹ h ⁻¹)					
	In Air			In 3% O ₂		
	0°C	10°C	20°C	0°C	10°C	20°C
Beetroot						
Storing	4	11	19	6	7	10
Bunching with leaves	11	22	40	7	14	32
Carrots						
Storing	13	19	33	7	11	25
Bunching with leaves	35	74	121	28	54	85
Onion (Bedfordshire champion)	3	7	8	2	4	4
Potato						
Maincrop (King Edward)	6	4	6	5	3	4
“New” (immature)	10	20	40	10	18	30

Source: [1].

the transient regimes of temperature such as during loading or unloading of storages. In Table 2.2 an overview is given of the respiration activity of some root products at different gas compositions and temperatures.

Respiration results in the utilization of substrate (e.g., glucose) and oxygen and the formation of carbon dioxide, water, and energy. Knowing the rate of respiration (milligrams CO₂ produced per kilogram of product per hour), the rate of dry-weight loss and the amount of heat and metabolic water produced can be calculated. Examples of these calculations for carrots are illustrated in Fig. 2.3.

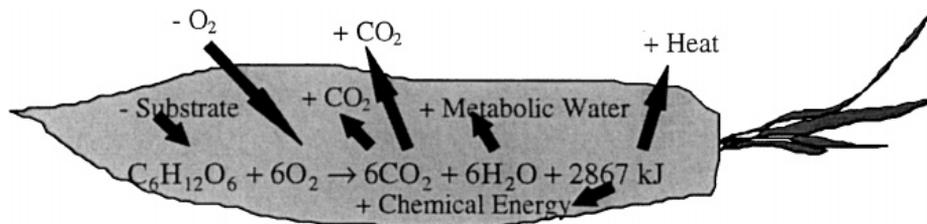
2.1.3 Water Loss of Stored Products

Transpiration

Transpiration of root crops is a mass transfer process in which water is lost from the product. It involves the transport of moisture through the outer layers of the product, the evaporation of the moisture from the product surface, and the convective mass transport of the moisture to the surroundings. Moisture loss affects the product quality, causing changes in appearance (the surface starts to shrivel), texture, and flavor. In addition, moisture loss also reduces the mass of salable product. The driving force for transpiration is the vapor-pressure difference between the surface of the product and the surrounding air. The basic mathematical model to describe transpiration is given by:

$$\dot{m}_w = k_t(P_s - P_a) \quad (2.5)$$

where \dot{m}_w is the moisture loss per unit product surface, P_a and P_s are the vapor pressure in the surrounding air and at the product surface, respectively, and k_t is the transpiration coefficient. To take into account the skin resistance of the product and the effect of airflow



Carrots are stored at 10°C and have a respiration rate of 19 mg CO₂ /kg hr

TRANSPIRATION WEIGHT LOSS

Carrots have a transpiration coefficient of 1648 ng/s.Pa.kg

The daily transpiration loss is equal to :

$$m_w = 1648 \times (P_s - P_a) \times \frac{3600}{1000} \times 24$$

$$P_s = 10^{(2.7857 + \frac{7.5T}{237.3+T})} \text{ Magnus formula}$$

$$P_a = P_s \cdot \frac{RH}{100}$$

When the surrounding air is at 10°C and a relative humidity (RH) of 90% and 98%, this results in a daily transpiration weight loss of 17 g/kg day and 3.49 g/kg day, respectively.

RATE OF DRY WEIGHT LOSS

For every 180 g of sugar oxidised, 264 g of CO₂ is produced by the product. Therefore, the rate of dry matter loss in grams of glucose/kg is equal to :

$$\left[\frac{19 \text{ mg CO}_2 / \text{kg} \cdot \text{hr}}{1000 \text{ mg} / \text{g}} \right] \left[\frac{180}{264} \right] \left[\frac{24 \text{ hr}}{\text{day}} \right] = 0.31008 \text{ g} / \text{kg} \text{ day}$$

HEAT PRODUCED BY RESPIRATION

$$19 \text{ mg} / \text{kg} \cdot 10.7 \cdot 24 = 4878 \text{ J} / \text{kg} \text{ day}$$

METABOLIC WATER PRODUCED

Ratio of weight CO₂ to weight water produced is 264/108. Therefore, the carrots produce the following metabolic water :

$$\frac{264 \text{ g CO}_2}{108 \text{ g H}_2\text{O}} \times \frac{19 \text{ mg CO}_2 / \text{kg} \cdot \text{hr}}{\text{x mg H}_2\text{O} / \text{kg} \cdot \text{hr}} \times 24 \text{ hr} = 186 \text{ mg H}_2\text{O} / \text{kg} \text{ day}$$

TOTAL WEIGHT LOSS

The total weight loss of carrots in one week is :

	90 % R.H.	98 % R.H.
Respiration		0.31008 x 7 g/kg week
Transpiration	17 x 7 g/kg week	3.5 x 7 g/kg week
Total weight loss	121.17g/kg week	26.64 g/kg week

Figure 2.3. Example of weight loss of carrots by respiration and transpiration.

rate, the transpiration coefficient is modified as follows [5]:

$$\frac{1}{k_t} = \frac{1}{k_a} + \frac{1}{k_s} \quad (2.6)$$

The convective mass transfer at the surface, k_a , is a function of the airflow rate. The skin mass-transfer coefficient k_s accounts for the diffusional resistance of the skin towards moisture migration. The skin mass-transfer coefficient is dependent on the product type and may vary over the surface. Crops with a cuticle have a low skin mass-transfer coefficient except if they have sufficient stomatas. Roots and tubers with a periderm with living cells have a high mass-transfer coefficient. After suberization, the potato periderm has layers of cork cells that offer some protection from moisture loss and have a lower mass-transfer coefficient.

The fact that only a fraction of the product surface may be permeable for water vapor sometimes is specified explicitly in the expression for the transpiration coefficient [6]:

$$\frac{1}{k_t} = \gamma \left(\frac{1}{k_{\text{ext}}} + \frac{1}{k_{\text{int}}} \right) \quad (2.7)$$

where γ is the fraction of the surface permeable for water vapor, k_{ext} is the external mass transfer coefficient, and k_{int} is the internal mass transfer coefficient. The latter depends on the internal (skin-layer) diffusion coefficient for water vapor and also on the vapor-pressure difference inside and outside the product [7].

In model calculations it is convenient to use values of k_s that have been obtained experimentally [8, 9]. Values for the convective mass transfer coefficient at the surface are calculated from the Sherwood-Reynolds-Schmidt correlation [8]:

$$Sh = 2.0 + 0.552 Re^{0.53} Sc^{0.33} \quad (2.8)$$

where Re is the Reynolds number, Sc is the Schmidt number, and Sh is the Sherwood number

$$Sh = k_a + \frac{d}{\delta}$$

where δ is the diffusion coefficient of water vapor in air. Values of skin mass-transfer coefficients are given in Table 2.1.

In storage conditions in which natural convection is significant, the airflow rate is caused by internal heat generation and by evaporative cooling resulting from transpiration. A higher fraction of surface permeable to water results in a higher rate of total moisture loss and thus in lower temperature differences and lower air velocities under steady-state conditions [6]. Also, it seems better to have a large porosity of the bulk stored product. This results in a lower maximum temperature, while the total rate of moisture loss appears to be only slightly affected.

Water Potential and Internal Water Status

Instead of the use of moisture concentrations to describe the internal water status of root crops, the concept of water potential often is preferred. The concept is based on the

chemical potential of water and is defined as follows:

$$\psi = \frac{\mu - \mu_{\text{ref}}}{V_w} \quad (2.9)$$

where ψ is the water potential (Pa), μ is the chemical potential of water of the system in question (J mol^{-1}), μ_{ref} is the reference value of the chemical potential of water (J mol^{-1}), and V_w is the molal volume of water, given as $0.000018 \text{ m}^3 \text{ mol}^{-1}$.

Equations to determine water potential for air, ψ_{air} , and solutions, ψ_{sol} , are [10]:

$$\psi_{\text{air}} = (RT/V_w) \ln(\text{RH}/100) \quad (2.10)$$

and

$$\psi_{\text{sol}} = (RT/V_w) \ln N_w \quad (2.11)$$

where R is the gas constant, T the absolute temperature, RH the relative humidity, N_w the molal fraction of water of the solution, and V_w the constant molal volume of water.

The water potential of a system ψ potentially can be subdivided into a number of potentials, including the vapor potential ψ_v , osmotic potential ψ_o , turgor potential ψ_t , matrix potential ψ_m , and gravitational potential ψ_g :

$$\psi = \psi_v + \psi_o + \psi_t + \psi_m + \psi_g \quad (2.12)$$

For a description of the water status of plants, the osmotic and turgor potential are of primary importance; the other factors can largely be neglected. Consider a plant cell and the interstitial moisture around the cell. Because the water in the cell cytoplasm contains a higher concentration in solutes than the water outside the cell, the osmotic potential of the cytoplasm is more negative than the osmotic potential outside the cell. This difference in osmotic potential causes moisture to migrate through the semipermeable cell membrane into the cell.

The process of moisture migration into cells continues until the turgor potential, associated with the turgor pressure created by the rigid cell wall of plant cells, equals the osmotic potential. At this point, a hydrostatic equilibrium is reached. Conversely, if the transpiration is excessive, water diffuses out of the cells into the interstitial spaces due to a reversed water potential, and the turgor potential drops. The product loses its turgidity and firmness.

Transfer of Moisture During Transpiration

If a root, tuber, or bulb is exposed to air, moisture loss to the surroundings may take place. Although it is tempting to say that the driving force for the transfer of moisture to the air is the gradient in moisture concentration, the correct explanation is that the product possesses a higher water potential than the air and that moisture migrates from a high water potential to a low water potential. It is therefore clear that moisture in a root migrates towards the surface, where it subsequently evaporates into the surrounding air. The following differential equation can be used to describe the migration of moisture in root crops [10]:

$$\frac{\partial M}{\partial t} = \nabla k_m \nabla \psi. \quad (2.13)$$

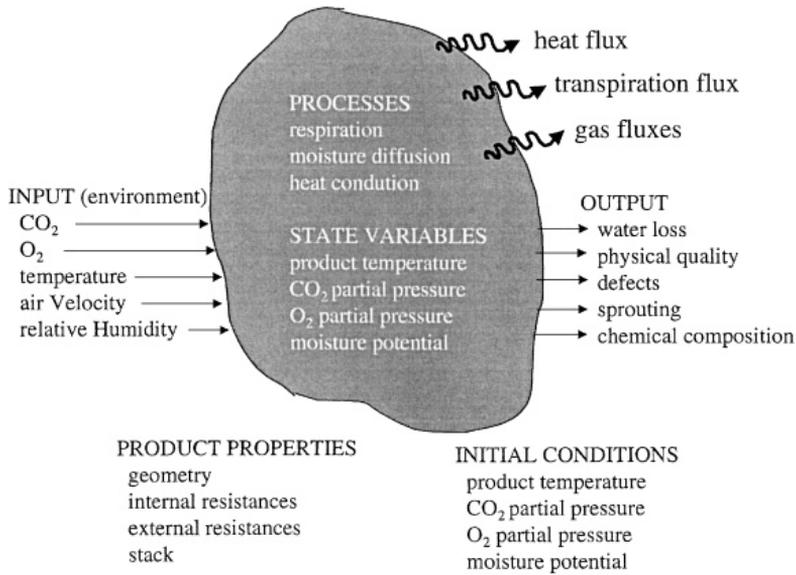


Figure 2.4. Transpiration of root crops: related factors and phenomena. (Source: [4])

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Initial conditions are

$$\psi(t = 0) = \psi_o. \quad (2.14)$$

Convective boundary conditions are

$$k_m \frac{\partial \psi}{\partial n} = h_m (\psi_a - \psi) \quad (2.15)$$

where M is the moisture concentration ($[\text{kg moisture}][\text{kg dry matter}]^{-1}$), ψ the water potential ($^{\circ}\text{M}$), ψ_o the initial uniform water potential ($^{\circ}\text{M}$), ψ_a the water potential of the air ($^{\circ}\text{M}$), k_m the moisture conductivity ($\text{kg moisture} \cdot \text{m}^{-1} \text{s}^{-1} \text{ } ^{\circ}\text{M}^{-1}$), h_m the convective mass transfer coefficient ($\text{kg m}^{-2} \text{s}^{-1} \text{ } ^{\circ}\text{M}^{-1}$), t the time (in seconds), and n the outward normal to the surface.

The system of equations contains two unknown variables: the moisture concentration M and the water potential ψ . In order to solve the equations, knowledge of the relationship between M and ψ at a specific temperature is required.

It is simplistic to assume one value of k for each type of root crop. The periderm (for roots and tubers) and dried outer leafs (for bulbs), which function as physical barriers against dehydration, have much smaller moisture conductivities than the rest of the root crop and should be taken into account when applying the model.

2.1.4 Heat Transfer of Root Products

It has been mentioned that the product temperature influences the metabolic processes of respiration and transpiration. As a consequence, the temperature history of the product

affects the quality of the product after storage. One of the most important steps after harvest is the removal of heat stored in the product. Indeed, at harvest time the product is at a temperature at which the respiration rate is high and the quality degrades rapidly. Although one could consider modeling the simultaneous heat and mass transfer inside the product, it may be more adequate to uncouple these two phenomena and address heat transfer separately. Heat transfer inside the product can be described by the Fourier equation, a partial-differential equation involving the change in heat content as a function of temperature and heat generation [27]:

$$\rho_p c_p \frac{\partial T_p}{\partial t} = \nabla(k_p \nabla T_p) + q_{\text{resp}} \quad (2.16)$$

$$T_p(x, y, z, t) = T_{p,\text{ini}}(x, y, z) \quad \text{at } t = t_0 \quad (2.17)$$

where ρ_p is the product density (kg m^{-3}), c_p the specific heat capacity, ($\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), k_p the thermal conductivity ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$), T_p the temperature ($^\circ\text{C}$), $T_{p,\text{ini}}$ the initial temperature ($^\circ\text{C}$), t time (s), t_0 initial time (s), x , y , and z Cartesian coordinates (m), and q_{resp} the volumetric specific respiration rate (W m^{-3}). Also:

$$q_{\text{resp}} = \frac{\rho_p Q_{\text{resp}}}{3600} \quad (2.18)$$

where Q_{resp} is the specific respiration rate ($\text{J hr}^{-1} \text{kg}^{-1}$).

In order to obtain the temperature distribution inside the root product as a function of time, the boundary conditions describing the energy transfer at the product surface Γ_s should be specified.

The different terms in the boundary conditions can be heat transfer by radiation (q_{rad}), either absorbed or released to the surroundings:

$$q_{\text{rad}} = \varepsilon \sigma (T_s^4 - T_w^4) \quad (2.19)$$

where ε is the emissivity, σ the Stefan-Boltzmann constant ($\text{W m}^{-2} \text{ }^\circ\text{C}^{-4}$), T_s the surface temperature ($^\circ\text{C}$), and T_w the surrounding temperature; heat lost or gained by convection:

$$q_{\text{conv}} = h(T_s - T_a) \quad (2.20)$$

where h is the surface heat transfer coefficient ($\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$), T_s the surface temperature ($^\circ\text{C}$), and T_a the ambient (air) temperature.

Heat lost or gained as latent heat of evaporation or condensation:

$$q_{\text{evap}} = \dot{m}_w (c_m T_s - c_v T_a - h_{fg}) \quad (2.21)$$

where \dot{m}_w is the moisture loss per unit surface ($\text{kg s}^{-1} \text{m}^{-2}$), h_{fg} the latent heat of vaporization of water (J kg^{-1}), c_m the specific heat capacity of the moisture in the product ($\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), T_s the surface temperature ($^\circ\text{C}$), c_v the specific heat capacity of the vapor in the air ($\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), and T_a the ambient (air) temperature ($^\circ\text{C}$); or heat lost or gained by conduction to other units or to the side walls of the container or of the storage room:

$$q_{\text{cond}} = -k_{\text{cont}} \frac{\partial T_{\text{cont}}}{\partial n} \Big|_{\text{at contact point}} \quad (2.22)$$

Table 2.3. Thermal conductivity of some root crops

	Water Fraction (wet basis)	Apparent Density (kg m^{-3})	Temperature ($^{\circ}\text{C}$)	Thermal Conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)
Potato	0.763	1127	40.0	0.410
Potato	0.763	1117	50.0	0.470
Potato	0.763	1121	60.0	0.460
Potato	0.763	1105	70.0	0.510
Potato	0.763	1107	80.0	0.560
Potato	0.763	1103	90.0	0.560
Potato	0.788	1166	50.0	0.510
Potato	0.763	1115	—	0.470
Potato	0.754	1139	—	0.410
Potato	0.723	1088	—	0.360
Potato	0.835	—	25.0	0.563
Potato	0.835	—	75.0	0.622
Potato	0.835	—	105.0	0.639
Potato	0.835	—	130.0	0.641
Onion	0.873	970	28.0	0.574
Beet (Red, Detroit)	0.895	1530	28.0	0.601
Carrot (Danver)	0.900	1040	28.0	0.605
Carrot	0.923	—	25.0	0.571
Carrot	0.923	—	70.0	0.620
Carrot	0.923	—	105.0	0.649
Carrot	0.923	—	130.0	0.664

Adapted from [11].

where k_{cont} is the wall thermal conductivity ($\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$), T_{cont} the wall temperature ($^{\circ}\text{C}$) and n the outward normal to the surface.

The thermal conductivity of some root products is given in Table 2.3. The data are based mainly on experiments [11]. It is possible to approximate the values of these properties for a given product if the chemical composition of the product is known [12].

For simple geometry and linear boundary conditions, the analytical solution of the heat-transfer equation (2.16) is available and can be found in textbooks on heat transfer [13–16]. In general, root crops are complex-shaped products with temperature-dependent material properties (ρ_p , k_p , c_p) and are subjected to nonlinear or time-varying process conditions. No analytical solutions are available for such complicated heat-transfer processes, and an approximate solution technique becomes mandatory. In practice, a numerical solution of the heat equation (2.16) can be obtained by means of finite-difference or finite-element methods. Several finite-difference or finite-element computer programs are available commercially and on the World Wide Web or can be found in the scientific literature. When considering heat transfer problems with complex-shaped products and complex boundary conditions, the finite-element method is better suited and more advised [17–19].

As an example, the cooling of a carrot is considered. The modeling procedure requires a geometrical description of the carrot in terms of geometric primitives such as keypoints, lines, areas, and volumes.



Figure 2.5. Geometrical model of a carrot, constructed by use of computer vision tools [20].



Figure 2.6. Finite-element mesh of a cross-section of a carrot.

In mechanical- and civil-engineering applications a geometrical model of the structure to be analyzed is usually available as a computer-aided design, and it can be imported directly in the finite element software. For agricultural, biological, and food materials such geometrical models are not available and must be defined manually, which can be complicated because of the complex shape and shape variability. As a consequence, often a simplified geometrical model of the object is used and many important details are lost. Computer vision is a powerful and challenging tool to overcome these difficulties. In Fig. 2.5 a geometrical model of a carrot is shown, which was constructed by use of computer-vision tools [28]. A finite-element mesh of a cross-section of that carrot is shown in Fig. 2.6. The global finite-element grid consist of 3761 nodes and 2112 quadratic isoparametric tetrahedral elements.

For the simulations, the thermophysical properties of the carrot were used [21]. The initial temperature and the heat transfer coefficient were set at 20°C and $20\text{ W m}^{-2}\text{ }^{\circ}\text{C}^{-1}$, respectively. The ambient temperature was assumed to fluctuate between 0 and 4°C .

In Fig. 2.7 the computed time-temperature profiles at different locations in a carrot under fluctuating ambient temperature conditions are outlined. The finite-element technique offers a powerful tool for the investigation of heat transfer of root products and for the optimization of the design and control of cooling systems.

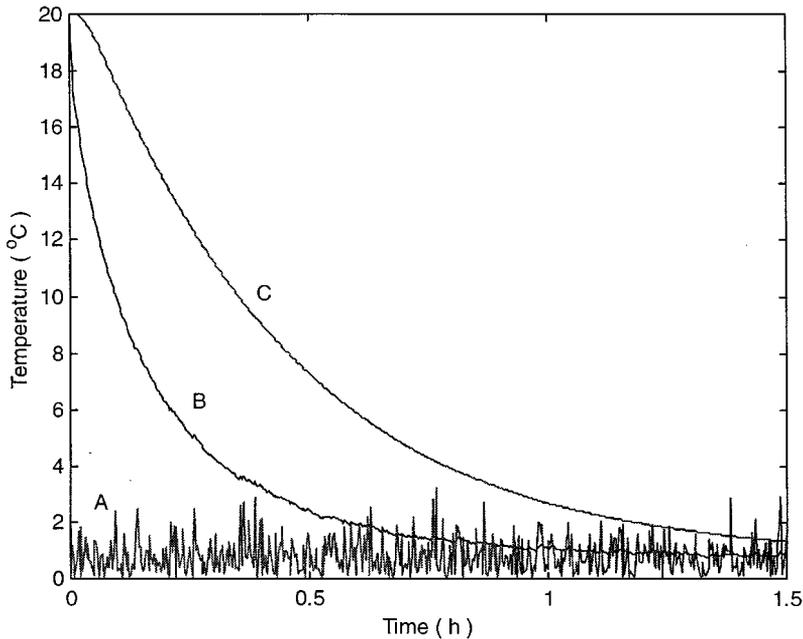


Figure 2.7. Time-temperature profiles for the cooling of a carrot at different locations. A, ambient temperature; B, coldest points; C, warmest point.

2.1.5 Modeling Heat and Moisture Transfer in Forced Convection Bulk-Product Storage

In the previous paragraphs considerable attention was given to heat and mass transfer within individual root particles and to the relation of heat and mass transfer with metabolic processes. In this subsection, the bulk product in a container or in a storage room is considered. Therefore, the airflow and the heat and mass exchange between the products and the surrounding air must be taken into account. The modeling helps to understand the effects of storage size and shape or dimensions of containers on the temperature and moisture distribution (and product quality) at different locations in the store. A one-dimensional approach is given here in the hope that this will encourage the reader to further explore the modeling process to improve the understanding of the interaction between physical and physiological processes occurring during product storage. It will become clear that the model development is based on the heat and mass transfer equations derived in previous paragraphs for individual roots or tubers.

Several approaches have been published for modeling the cooling in bulk stored products in order to forecast the temperature and moisture evolution in the stack and the individual products. These models have some similarity with the models developed for grain drying, but some important differences exist. The most extensive model representation [22] involves a two-phase model with internal temperature gradients for the solid phase, that is, for the product. Evaporative heat losses at the surface and internal heat generation

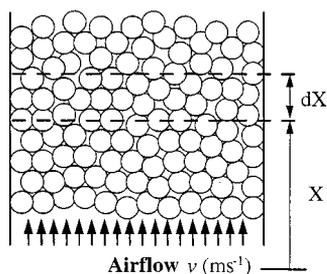


Figure 2.8. Schematic representation of a one-dimensional cooling of root products.

with linear temperature dependence are included, although a nonlinear model would be more appropriate. Moisture loss is described with the two-term model including condensation on the product. Heat conduction from product to product is considered negligible. The use of moisture gradients inside the product often is deemed unnecessary during cooling of bulk-stored produce because of the high moisture content and the low moisture loss.

In the subsequent paragraphs, a model for cooling of bulk stored products is presented. It does not include airflow by natural convection, although natural convection may play an important role in the temperature and moisture distribution in the store. Modeling of natural convection is discussed later.

If the individual root-crop particles are relatively small compared to the stack height, a differential equation or continuum approach can be used for a 1-m² cross-section of the stack. A schematic representation is given in Fig. 2.8.

The stack is composed of product (subscript *p*) and of air (subscript *a*). The product temperature,

$$T_p = T(X_i, x_i, t), \tag{2.23}$$

can vary with the position X_i in the stack and also inside a single particle (x_i). For the heat exchange with the air flowing through the stack, only the particle surface temperature T_s is needed. The surface heat transfer contributes a boundary condition for the intraparticle heat transfer.

The number of particles n_p in a differential volume,

$$\Delta V = A \Delta x = 1 \Delta x, \tag{2.24}$$

is equal to

$$n_p = (1 - \varepsilon) \Delta V / V_{p,av} \tag{2.25}$$

where ε is the stack porosity and $V_{p,av}$ is the average single particle volume. The heat and moisture transfer taking place between the product and the air inside a differential element is proportional to the particle surface inside the element. This is given by the

number of particles (n_p) multiplied by the average particle surface area $S_{p,av}$:

$$\Delta A_p = n_p S_{p,av} \quad (2.26)$$

The velocity v_a of the air in the stack is a function of the porosity and of the entrance air velocity v_a^* :

$$v_a = v_a^*/\varepsilon. \quad (2.27)$$

With this velocity v_a , the average surface heat transfer h_{av} and air film mass-transfer coefficient k_a can be calculated. The temperature and moisture content of the air changes with time and place as a result of the transport processes at the particle surface:

$$\rho_a v_a \frac{\partial M_a}{\partial X} + \rho_a \frac{\partial M_a}{\partial X} = r_v \quad (2.28)$$

$$v_a \frac{\partial T_a}{\partial X} + \frac{\partial T_a}{\partial t} = \frac{-h_{av} \Delta A_p (T_a - T_s) - r_v c_v (T_a - T_v)}{\rho_a (c_a + c_v H)} \quad (2.29)$$

where T_a is the air temperature ($^{\circ}\text{C}$), T_v the mean evaporation temperature for water ($^{\circ}\text{C}$), U the moisture content of the air or absolute humidity (kg kg^{-1}), ρ_a the air density ($\text{kg}\cdot\text{m}^{-3}$), c_a the specific heat capacity of dry air ($\text{J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$), c_v the specific heat capacity of moisture in the air ($\text{J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$), c_p the specific heat capacity of the product ($\text{J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$), and h_{fg} the latent heat of vaporization of water (J kg^{-1}).

The right-hand side of Eq. (2.28) is the moisture loss of the product:

$$r_v = \Delta A_p k_t (P_s - P_a) = \dot{m}_w \Delta A_p \quad (2.30)$$

where P_s (N m^{-2}) is the surface vapor pressure and P_a the air vapor pressure (N m^{-2}). Note that the mean temperature for evaporation of water T_v can be either the air temperature T_a , the product surface temperature T_s , or the average of T_a and T_s .

The water-vapor pressure can be calculated from the humidity ratio and the air temperature [23]:

$$P_a = P_a(M, T) \quad (2.31)$$

What remains to be calculated are the product surface temperature T_s and the surface vapor pressure P_s . If one neglects moisture gradients inside the root particle, then P_s can be considered to be the saturated vapor pressure at the product surface temperature T_s . Some modifications may be needed because dissolved substances, such as sugars, cause a vapor-pressure lowering effect on the product surface.

If substantial internal moisture migration occurs, the partial-differential equation for moisture transfer inside the product must be solved for an average particle inside the differential volume (see the paragraph on water movement in products). These calculations require a considerable amount of computational effort.

The product surface temperature T_s in Eq. (2.29) is obtained from the solution of the Fourier equation for heat transfer inside the product particle at location X . The boundary conditions consist of the heat transfer by convection and the product heat loss caused by

evaporation:

$$-k \frac{\partial T}{\partial x} \Big|_s = h(T_s - T_a) + \dot{m}_w(c_m T_s - c_v T_a - h_{fg}) \quad (2.32)$$

where T_s is the product surface temperature. At the top of the stack it may be required to include the radiation boundary conditions. Note that the heat-transfer calculation inside a particle requires considerable computational effort, as it must be executed at each location for each time step. In addition, the internal particle temperature must be recorded for each location. The changing air temperature T_a means that the boundary conditions are dependent on time and place. Nevertheless, this additional effort provides a more realistic product time–temperature history.

From the metabolic processes, an assessment can be made of the product quality change during storage. The quality evolution may vary considerably with the location in the stack.

2.1.6 Natural Convection inside Stores

Heat produced by the product and heat losses through the sidewalls or the top of the stack induce temperature differences in the air. This gives rise to natural convection. Differences between water-vapor concentrations in the air inside and outside the stack or even within the stack itself cause density differences in the air, resulting in natural convection.

Natural convection in closed moist porous media causes heat and moisture transfer and sometimes leads to local areas of condensation, resulting in product spoilage. Natural convection is difficult to control, because the outside temperature can vary from one wall to another and also changes with time.

Modeling natural convection inside stores containing agricultural products has received some attention [6, 24]. The computational complexity is a major hindrance. Recently, some progress has been made in computational fluid dynamics, and improved modeling can be expected for heat and mass transfers by natural convection inside stores of agricultural products.

A simplified approach is to derive a model for the “superficial” natural-convection velocity of the air v_{NC} in the stack (this is not known a priori). The equation can then be coupled to a system of equations as described above. The velocity must be obtained from information regarding the effect of the density changes resulting from heating or moisture changes in the bulk. In a one-dimensional quasistatic analysis, the following relation is obtained [6]:

$$v_{NC} = -\frac{\kappa}{\mu} \left(\frac{dP}{dX} + \rho g \right). \quad (2.33)$$

Equation (2.33) results from the linear conservation equation of momentum, in which the inertia term is neglected due to the small velocity. The viscous term is replaced by the Darcy approximation.

Assuming a linear variation of the density with temperature and water-vapor concentration C , and given that the pressure drop over the bulk is caused by the weight of the

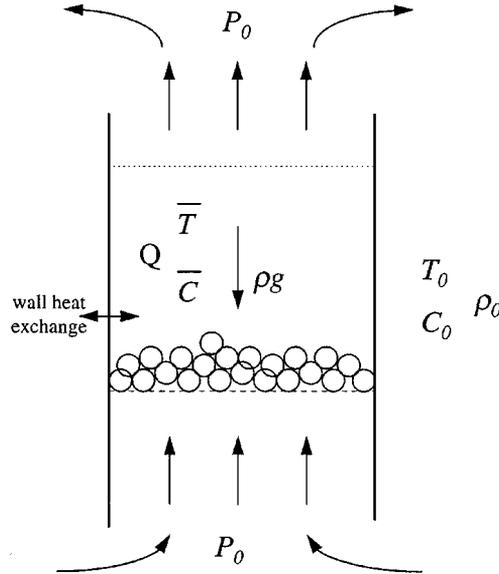


Figure 2.9. Simple one-dimensional natural-convection analysis with pervious top and bottom.

air only (Fig. 2.9), the natural-convection velocity becomes

$$v_{\text{NC}} = \frac{\kappa}{\mu} \rho_0 g (\beta_T (\bar{T} - T_0) - \beta_C (\bar{C} - C_0)) \quad (2.34)$$

where the index 0 refers to the reference conditions, such as the outside air.

The permeability κ , resulting from Darcy's law, can be obtained from a model of the pressure drop in a porous medium or packed bed. It is constant for very low fluid velocities. A velocity-dependent permeability has been proposed by several authors [25, 26]. The following modified Ergun equation produces good results:

$$\kappa = \frac{\varepsilon^3 d_p^2}{K(1 - \varepsilon)(150[1 - \varepsilon] + 1.75 Re)} \quad (2.35)$$

where d_p is the mean particle diameter and Re the Reynolds number. To obtain the velocity, the expression can be evaluated using the average temperature and concentration distributions in the system. In the next time step, the velocity can be used to calculate the new temperature and concentration distribution. The previously mentioned formula limit the analysis to the simple case of unidirectional, convective transport, restricting the applicability of the model in real cases. It can be applied to two-dimensional cases, when the diffusion occurs radially only [6], making it possible to evaluate the effect of heat losses through the walls. A vector notation of the expression in Eq. (2.34) and the full-energy equation can be used to model the three-dimensional natural convection flow [6]:

$$\vec{v}_{\text{NC}} = -\frac{\kappa}{\mu} (\nabla P - \rho_0 \vec{g} (1 - \beta_T (T - T_0) - \beta_C (C - C_0))) \quad (2.36)$$

The coupled set of equations can be solved to obtain the velocity, the temperature, and the moisture concentration at each location in the store for each time step. The numerical solution consumes much computer time. However, internal currents in the stack can be calculated so that more complex conditions can be investigated.

Recent advances in the development of flexible and user-friendly fluid-dynamics software packages and the increasing power of computers have opened the gate for future developments in this area. Powerful solution algorithms in combination with high-order finite-volume or finite-element discretization schemes are provided for the accurate numerical solution of the system of fluid-flow, energy, and mass-transport equations. When the full system of conservation equations (for forced as well as natural convection) can be applied to the entire store and its immediate surroundings, the restriction to simplified geometries and boundary conditions is no longer a hurdle, and an improved understanding of transport processes and consequent quality changes in the bulk storage of root crops becomes possible.

2.1.7 Quality Standards for Root Crops

Transport processes and physiological changes affect the quality of the root crop. Furthermore, mechanical impacts may injure the crop. Also, diseases can considerably reduce the value of a stored crop. The chemical and physiological mechanisms of the quality changes are beyond the scope of this section. Quality is described from the viewpoint of the consumer, and the standards for quality control are a result of the increased competition on the international market for agricultural products.

The quality of root-crop products is generally evaluated similarly to other fruit and vegetables. Thus, external properties such as appearance, shape, and size are considered primarily, while only limited specifications are given concerning internal quality. Government standards specify minimal requirements (e.g., in the European Union, see Table 2.4) and give a classification to distinguish tolerable defects (e.g., onion classification in Belgium, Table 2.5).

It is clear that some of these requirements are rather arbitrary and subject to different interpretations. Therefore, international regulations are continuously being amended to obtain a more uniform interpretation of the standards. Furthermore, traders and

Table 2.4. General minimum quality requirements for root crops

Product without damage
Free of spoilage symptoms
No parasites
Free of foreign material
Healthy
No strange smell or taste
No excessive moisture on the outside
Product condition and package can guarantee product quality up to destination point

Source: [27].

Table 2.5. Classification of onions

Class I
Onions of good quality
Color and shape are characteristic for the variety
Firm
Not sprouted
Without hollow stem
Free of thickenings due to abnormal growth
Free of root remainders
Class II
As class I, but with the following tolerable defects:
Sufficiently firm
Traces of friction
Small indications of decay
Small healed bruises that are not detrimental for the shelf life
Small healed cracks
Aberrant shape and color
Starting sprout
Class III
As class II, but with the following tolerable defects:
Root remainders
Beginning of sprout for up to 20% of onions in a package unit
Bruises not detrimental for the shelf life

Source: [28].

distributors have a tendency to use more stringent quality requirements to distinguish within the official classes of specific products.

References

1. Kays, S. J. 1991. *Postharvest Physiology of Perishable Plant Products*. New York: Van Nostrand Reinhold.
2. U.S. Department of Agriculture. 1986. The commercial storage of fruits, vegetables, and florist and nursery stocks. Agricultural Handbook Number 66. Washington, DC: Author.
3. Becker, R. B., and B. A. Fricke. 1996. Simulation of moisture loss and heat loads in refrigerated storage of fruits and vegetables. In *Refrigeration Science and Technology Proceedings*. October 2–4, 1996, Lexington, KT.
4. ASHRAE. 1993. *1993 ASHRAE Handbook: Fundamentals*. Atlanta: ASHRAE.
5. Fockens, F. H., and H. F. T. Meffert. 1972. Biophysical properties of horticultural products as related to loss of moisture during cooling down. *Journal of the Science of Food and Agriculture* 23:285–298.
6. Beukema, K. J. 1980. Heat and mass transfer during cooling and storage of agricultural products as influenced by natural convection. Ph.D. diss., Landbouwhogeschool, Wageningen, The Netherlands.

7. Villa, L. G. 1973. Single particle convective moisture losses from horticultural products in storage. Ph.D. diss., Michigan State University.
8. Chau, K. V., R. A. Romero, C. D. Baird, and J. J. Gaffney. 1987. Transpiration coefficients of fruits and vegetables in refrigerated storage. ASHRAE Report 370-RP. Atlanta: ASHRAE.
9. Gan, G., and J. L. Woods. 1989. A deep bed simulation of vegetable cooling. In *Agricultural Engineering*, ed. V. A. Dodd and P. M. Grace, pp. 2301–2308. Rotterdam: A.A. Balkema.
10. Merva, G. E. 1995. *Physical Principles of the Plant Biosystem*. St. Joseph, MI: ASAE.
11. Rahman, S. 1995. *Food Properties Handbook*, p. 296. CRC Press.
12. Miles, C. A., Van Beek, G., and Veerkamp, C. H. 1983. Calculation of thermophysical properties of foods. In *Physical Properties of Foods*, ed. R. Jowitt, F. Escher, B. Hallström, H. F. Th. Meffert, and W. E. L. Spiess. Vos G. Applied Science Publishers: London.
13. Bird, B. B., W. E. Stewart, and E. N. Lightfoot. 1960. *Transport Phenomena*. New York: John Wiley & Sons.
14. Özisik, M. N. 1980. *Heat Conduction*. New York: John Wiley & Sons.
15. Incropera, F. P., and D. P. De Witt. 1990. *Fundamentals of Heat and Mass Transfer*. New York: John Wiley & Sons.
16. Geankoplis, C. J. 1993. *Transport Processes and Unit Operations*. Prentice-Hall International; New Jersey.
17. Nicolai, B. M., P. Van den Broeck, M. Schellekens, G. De Roeck, T. Martens, and J. De Baerdemaeker. 1995. Finite element analysis of heat conduction in lasagna during thermal processing. *International Journal of Food Science and Technology* 30:347–364.
18. Scheerlinck, N., B. M. Nicolai, P. Verboven, and J. De Baerdemaeker. 1996. Finite element analysis of coupled heat and mass transfer problems with random field material properties. Paper No. 963028, ASAE Annual International Meeting, Phoenix, Arizona.
19. Scheerlinck, N., K. A. Fikiin, P. Verboven, J. De Baerdemaeker, and B. M. Nicolai. 1997. Numerical solution of phase change heat transfer problems with moving boundaries using an improved finite element enthalpy method. In *Computational Modelling of Free and Moving Boundary Problems IV*, ed. L. C. Wrobel, B. Sarler, and C. A. Brebbia. Boston: Computational Mechanics Publications.
20. Jancsó, P., B. M. Nicolai, P. Coucke, and J. De Baerdemaeker. 1997. 3D Finite element model generation of fruits based on image processing. 3rd IFAC/ISHS Workshop on Mathematical and Control Application in Agriculture and Horticulture, pp. 131–135, Hannover, Germany.
21. Product data of fruits and vegetables 1981. Mededelingen nr. 30. Wageningen: Sprenger Institute.
22. Lerew, L. E. 1978. Development of a temperature-weight loss model for bulk stored potatoes. Ph.D. diss., Michigan State University, Department of Agricultural Engineering.

23. Brooker, D. B. 1965. Non-linear airflow patterns in grain drying systems. Research bulletin 892, University of Missouri-Columbia, Agricultural Experiment Station.
24. Messaho, D. 1990. Mathematical modeling of associated transport phenomena in hygroscopic porous media: Application to grain storage. Ph.D. diss., Institut Agronomique et Veterinaire Hassan II, Rabat, Morocco.
25. Bakker Arkema, F. W., R. J. Patterson, and W. G. Bickert. 1969. Static pressure: Air flow relationships in packed beds of granular biological materials such as cherry pits. *Trans. ASAE* 12:134–136, 140.
26. Patterson, R. J., F. W. Bakker Arkema, and W. G. Bickert. 1971. Static pressure: Air flow relationships in packed beds of granular biological materials such as grain II. *Trans. ASAE* 14:172–174, 178.
27. Commission Regulation (EEC) No 2251/92 of 29 July 1992 on Quality Inspection of Fresh Fruit and Vegetables. 1992. *Official Journal of the European Commission* no. L219/9 (amended by Commission Regulation No. 785/93 of 31 March 1993).
28. Common quality norms for Fruits and Vegetables. 1976. Ceuterick, Leuven, Belgium: Ministerie van Landbouw, Bestuur der Economische Diensten, Dienst Teeltproducten.

2.2 Storage of Potatoes

A. van't Ooster

2.2.1 *Solanum tuberosum* [1]

The common potato (*Solanum tuberosum*) is one of around 150 tuber-bearing species of the genus *Solanum* (family *Solanaceae*). The potato, considered by most botanists a native of the Peruvian–Bolivian Andes, is one of the world's main food crops, differing from others in that the edible part of the plant is a tuber.

Underground the stems extend into structures called *stolons*. The ends of the stolons may enlarge greatly to form a few to more than 20 tubers, of variable shape and size, usually ranging in weight up to 300 g but occasionally to more than 1.5 kg per tuber. The tubers bear spirally arranged buds (eyes) in the axils of aborted leaves, of which scars remain. These buds may remain dormant after the tuber is fully grown, even under conditions favorable to development, for up to 10 weeks or more. They grow into plants identical to the plant that bore the tubers. Vegetative propagation of desired genetical characteristics is thus possible, and this method is always used commercially because of the great variation that results when plants are grown from true seed.

2.2.2 History of the Potato [1]

The potatoes cultivated in South America as early as 1800 years ago probably consisted of a mixture of varieties; in the same area today, as many as 60 varieties may be distinguished in a single village market. Encountered by the invading Spaniards, potatoes were introduced into Europe during the second half of the 16th century. By the end of the 17th century the newcomer was a major crop in Ireland, and by the end of the 18th it was a major crop in continental Europe, particularly Germany, and in the west of England.

yield (kg/ha)

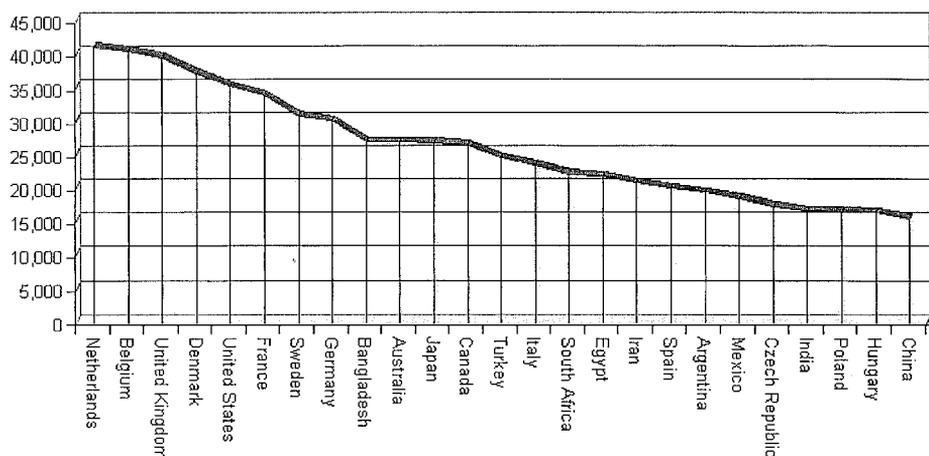


Figure 2.10. Countries with highest average yield per hectare. (Source: [1])

It continued to spread, in both Western and Eastern hemispheres, during the first four decades of the 19th century, but the disastrous failures of the Irish crops in the mid-19th century (especially in 1846 and 1848), because of late blight (*Phytophthora infestans*), and the ensuing famine led to a more cautious attitude towards dependence on it.

2.2.3 Potato Production

Table 2.6 and Fig. 2.10 give an impression of today's potato production in the world. Potatoes frequently are served whole or mashed as a cooked vegetable and also are ground into potato flour, used in baking and as a thickener for sauces. Potatoes are highly digestible. They also supply vitamin C, amino acids, protein, thiamin, and nicotinic acid. Potato product groups are seed potatoes; consumer potatoes, fresh and processed (fries and chips); and potatoes for industrial processing (starch and derivatives). Fig. 2.11 given an example of quantitative distribution over these product groups.

The product variety of potato products and derivatives grows steadily. In 1995 the world's production was 629,258,000 metric tons per year, which is a gross average of 109 kg per world inhabitant (5.75 billion people) [2]. These figures are not precise because potato-specific data are not available.

2.2.4 Importance of Product Storage

The main objectives of storage are future consumption, future processing, and maintenance of seed reserve. It allows a better use of processing capacity, better tuning of production and consumption, and better quality of seed potatoes.

Arable products such as potatoes belong to the group of semiperishable goods, that is, product with a high natural moisture content. These products are more sensitive to quality loss than cereals because conservation using drying techniques cannot be applied. Loss of moisture leads to (severe) quality loss and finally to nonmarketable produce. The

**Table 2.6. Production level of roots and tubers (potatoes and cassava)
in countries with a national production over one
million metric tons per year**

Country	Production (×1000 metric ton)	Yield (kg/ha)
Angola	1943	4396
Argentina	2410	19,195
Australia	1154	26,784
Bangladesh	1864	26,795
Belarus	8570	11,427
Belgium	2100	40,385
Benin	2447	9211
Bolivia	1004	5580
Brazil	29,009	12,963
Burundi	1326	6395
Cameroon	2080	5794
Canada	3774	26,273
China	152,813	15,342
Colombia	5164	12,926
Côte d'Ivoire	4761	5792
Czech Republic	1330	17,082
Denmark	1480	37,000
Egypt	1734	21,603
Ethiopia	2018	3679
France	5754	33,717
Germany	10,382	30,010
Ghana	10,382	11,339
Hungary	1151	16,262
India	26,300	16,386
Indonesia	18,603	11,790
Iran	3200	20,644
Italy	2076	23,281
Japan	5157	26,651
Kazakstan	1950	9142
Kenya	1685	8101
Korea, North	2050	12,059
Lithuania	1594	13,279
Madagascar	3375	6874
Mexico	1252	18,312
Mozambique	4310	4304
Netherlands	7363	41,002
Nigeria	56,006	10,613
Pakistan	1497	14,471
Papua New Guinea	1267	7073
Paraguay	2708	14,442
Peru	3369	9292
Philippines	22,820	6784
Poland	24,891	16,351
Portugal	1477	14,937
Romania	3020	12,080

(cont.)

Table 2.6. (Continued)

Country	Production ($\times 1000$ metric ton)	Yield (kg/ha)
Russia	37,300	10,941
Rwanda	1477	6864
South Africa	1524	21,925
Spain	4219	19,834
Sweden	1074	30,679
Tanzania	6670	7448
Thailand	18,382	13,995
Turkey	4750	24,356
Uganda	5246	5861
Ukraine	14,729	9621
United Kingdom	6445	39,405
United States	20,764	35,131
Vietnam	5077	7351
Zaire	18,358	8101
Other Countries	32,623	
World	629,258	

Source: [2].

risk of unacceptable moisture loss, disease spread, mold infections, and insect pests is obvious. Low storage temperature, high relative humidity, and control of air composition are the main conservation factors for this group of products. To guarantee a top-quality product, storage conditions must be well controlled; however, the market value does not allow full air conditioning. The storage should minimize physiological losses and losses due to mechanical damage. In tropical climates damage can originate from insects, like tuber moth, as well [5].

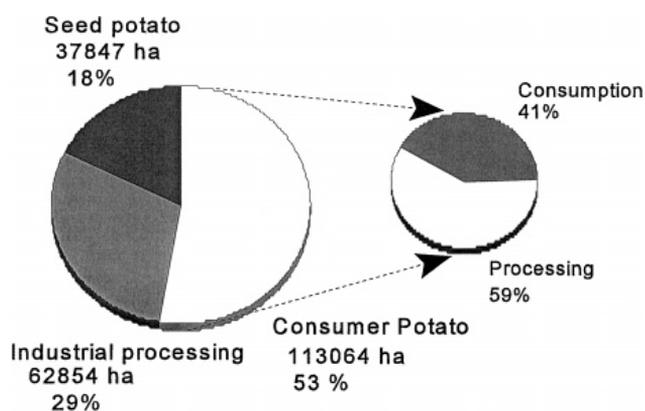


Figure 2.11. Dutch example of the destination of the potato production. Sources: [3, 4]

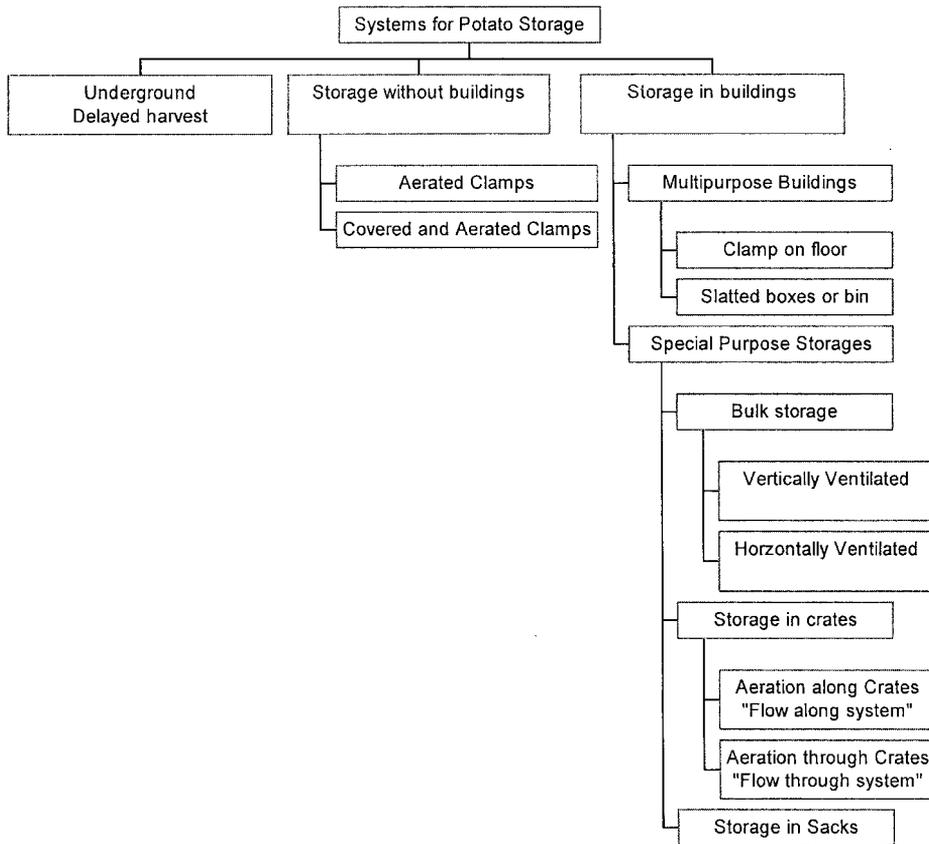


Figure 2.12. Overview of storage systems for potatoes.

2.2.5 Systems for Potato Storage

Systems used for potato storage all over the world are characterized in Fig. 2.12. We distinguish underground storage (extended harvest), storage without buildings in clamps, and storage in buildings [6]. Clamps predominantly are ventilated naturally. For storage in buildings mechanical ventilation prevails. Only the group storage in special-purpose stores with a mechanical ventilation system is discussed in more detail here.

We distinguish among bulk storage, storage in crates, and storage in sacks. Stores can be mechanically ventilated or naturally ventilated. Bulk storage can be vertically or horizontally ventilated (Fig. 2.13). Horizontal ventilation sometimes is applied to store potatoes for industrial processing. It is an underpressure system.

The aeration system is less complicated and cheaper, because an air-distribution system can be omitted. Although total airflow, for equal storage capacity, is the same for horizontally and vertically ventilated bulk stores, both airflow in the bulk, that is, the

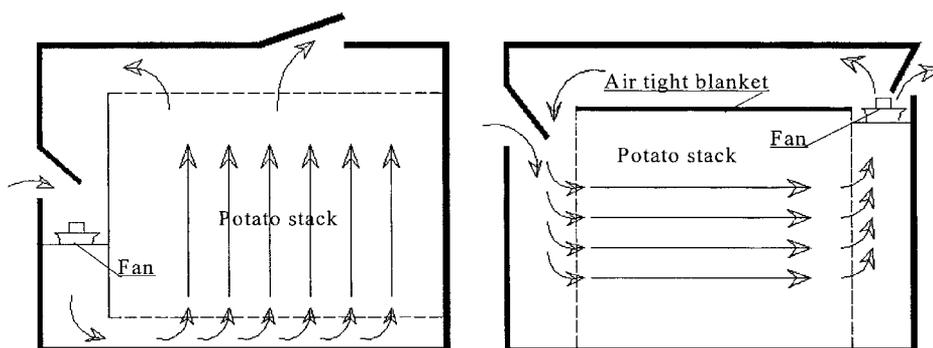


Figure 2.13. Schematic cross sectional view of vertically (a) and horizontally (b) ventilated potato stacks.

average air velocity in the bulk, and the pressure head are generally higher in horizontally ventilated bulk stores than in vertically ventilated bulk stores. Vertically ventilated bulk stores are generally designed as overpressure systems. This storage type holds the majority of today's potato harvest in the Western countries.

Risks and problems with bulk stores are [7]:

- A bulk height of 4 m or more can cause quality deterioration by bruising and black spots.
- Drying and cooling are not always fast enough, thus possibly causing weight and quality loss (soft rot, pathogen diseases).
- Separated storage of different lots, races, and selections, as is common with seed potatoes, is difficult.
- To prevent black spots induced by product handling, potato temperature must be 12°C or higher for sorting, packing, and transport operations. Bulk stores do not allow partial heating of a stored bulk.

For seed potatoes and potatoes for fresh consumption, crate storage in standard, 1-metric-ton crates can be interesting. Different varieties and lots can easily be managed for intermediate checking or handling. The effective stack height is the height of one box. Appropriate box sizes are ($l \times w \times h =$) 1.10 × 1.40 × 1.24 m. With crate storage drying can progress faster, resulting in a smaller chance of diseases and bruises. A better product quality may result. The "flow-along system" sends practically all ventilation air alongside of the crate, while the "flow-through system" forces ventilation air through the crates, thus showing a more effective use of the ventilation air, because heat and moisture exchange occur directly at the tuber's surface. The crates have closed side walls and a closed pallet bottom (Fig. 2.14). The crate floor is perforated to allow air to flow through.

The pallet bottom functions as an aeration channel (Fig. 2.15A). Stack height is up to five crates. A variant of single-layer aeration is double-layer aeration, in which every second pallet bottom is an air-input channel and every other (odd numbers) functions as an air-output channel (Fig. 2.15B).



Figure 2.14. Crate storage system with flow-through ventilation system. (Source: [7])

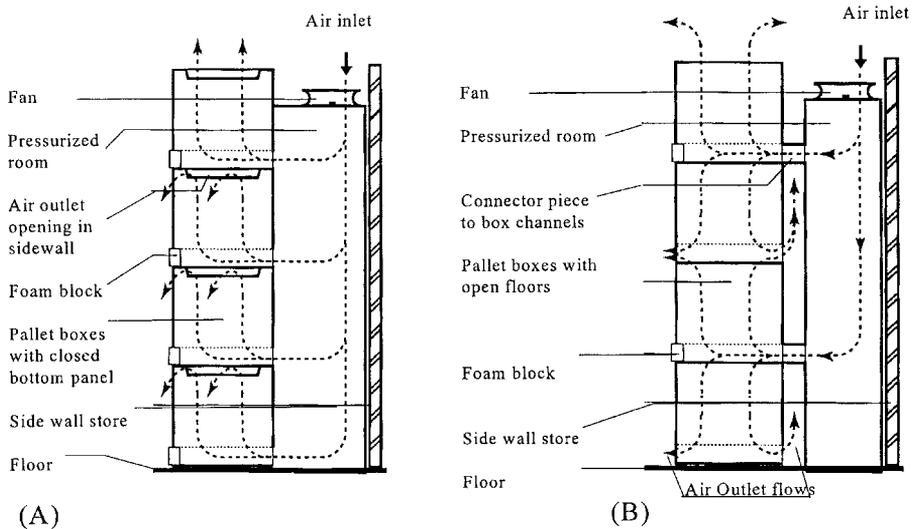


Figure 2.15. Single-layer aeration (A) and double-layer aeration (B) in crate storage systems.

Stack height is normally four crates. The distance between crate rows should at least be 10 cm. The flow-through system can be used for any potato type. To allow a reasonable air distribution rows should not be longer than nine crates for single-layer aeration and not longer than five crates for double-layer aeration.

The flow-along system is only suitable for dry and sorted potatoes. The crates should have open walls and floors and should be placed in rows of no more than 15 m. The distance between crate rows and between the outer crate rows and storage side walls should be at least 100 mm. At the fan side and at the opposite side in the length direction of the rows the minimal distance between crates and storage side wall should be 300 mm. Air coolers, ceiling channels, or vertical aeration tubes must allow equal distribution of ventilation air over the top layer (Fig. 2.16).

Storage in bags is only used for seed potatoes. Bags are piled up to heights of up to 5 m.

Storage Design

Thermal insulation of a store is necessary for proper control of the storage conditions. Free heat exchange between the storage room and the outdoor environment is then limited, and surface condensation on walls or ceilings can be prevented or strongly limited [8]. Not only is the insulation level of the materials used important, but also the attachment and design of joints are very important. Generally used insulation materials are polystyrene, polyurethane (plates or sprayed at location), and mineral wool. Materials differ in physical properties, such as density, heat conductance, vapor barrier and price.

The storage must be insulated in such a way that excessive heat losses in cold periods and excessive heat gains in warm periods as well as inner-surface condensation in cold periods are prevented. Generally for cold periods a U-value or heat-conductivity coefficient of $0.30 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ is suggested; for longer storage periods without use of mechanical cooling, $0.25 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ is suggested; and if mechanical cooling is applied $0.20 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for ceilings, $0.25 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for walls, and $0.50 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ for floors are suggested [9]. Solar heat loads on the roof can be minimized using reflective materials or a naturally aerated cavity or attic between roof cover and insulated ceiling.

Generally one should choose vapor barriers on the inside as well as on the outside of the insulation layer to prevent internal condensation in the insulation layer. This need for vapor barriers is dependent, however, on the external climate and the duration of the storage period. The building hood not only influences heat and moisture transport but also the exchange of oxygen and carbon dioxide.

Condensation on the building hood can be prevented by

- Decreasing the temperature difference between the inner surface of the building component and the air in the indoor airspace (that is the storage room). Prevent or insulate thermal bridges and choose a low U-value for building components. Another option is to install recirculating fans over the potato bulk to increase air movement and heat exchange between room air and building hood (Fig. 2.17).
- Decreasing the humidity ratio (kg vapor per kg dry air) in the air of the indoor airspace. This can be achieved by placing a moisture-absorbent layer on top of the

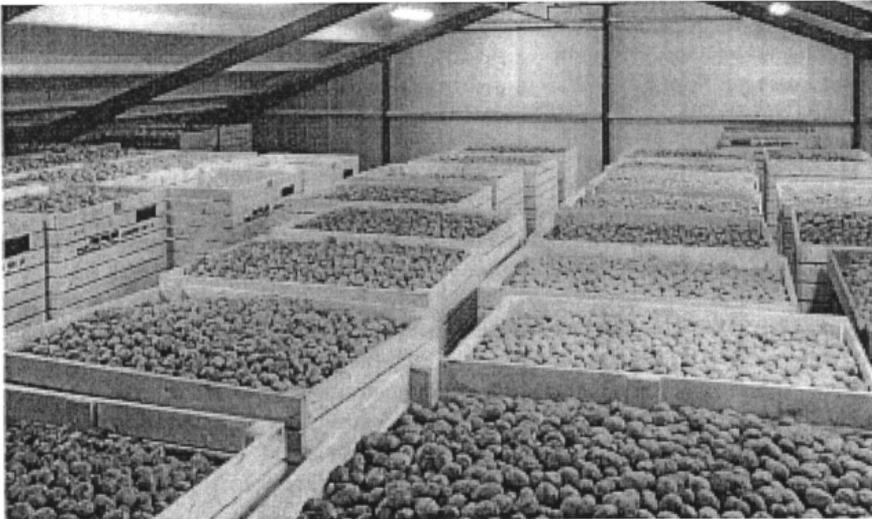
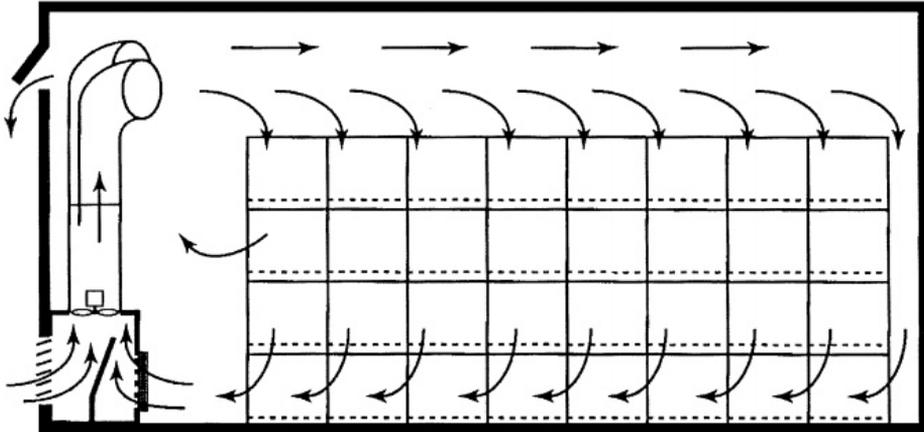


Figure 2.16. Crate storage system with flow along ventilation system.

potato bulk, or installing an anticondensation fan in the wall of the storage room in order to decrease humidity in times during which condensation risk is too high.

2.2.6 Phases in the Storage Period

In storage process we can distinguish among the following phases:

- I. Drying of wet product or removal of free water
- II. Suberization or wound healing (curing)
- III. Gradual cooling down to storage temperature
- IV. Long-term storage or holding period

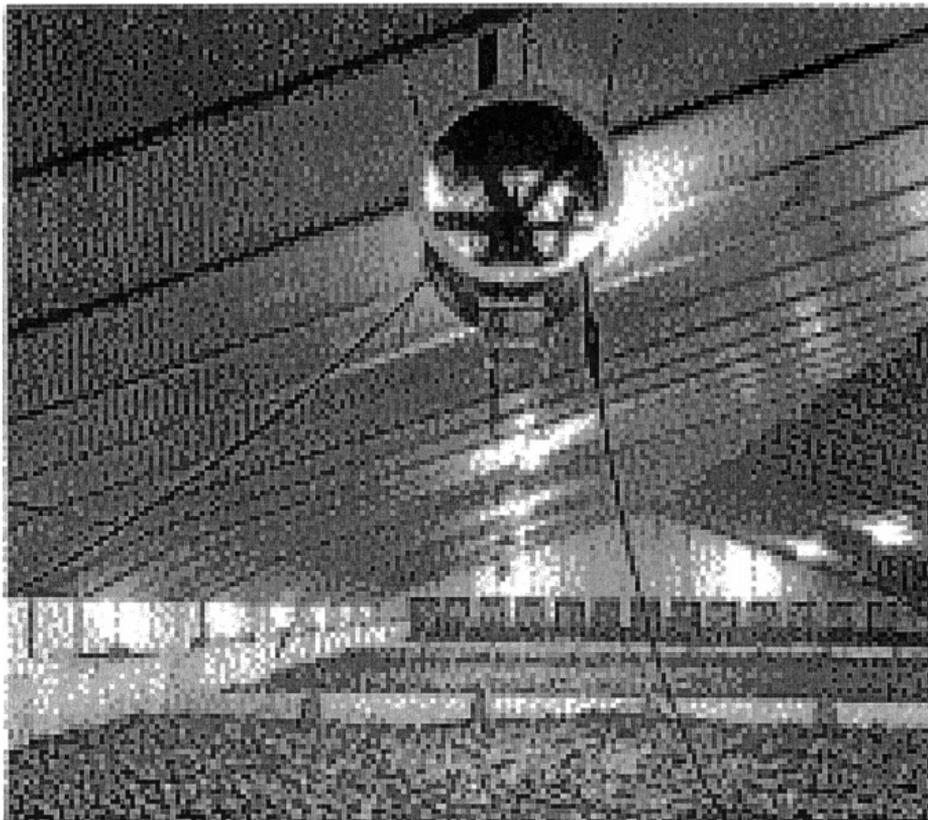


Figure 2.17. Fans recirculating storage-room air.

V. Heating up

VI. Reconditioning

Removal of Free Water

During drying the temperature of the potatoes should be between 12 and 20°C. The upper limit may not be exceeded to prevent sprouting and to minimize the chance on oxygen shortage in the tubers. Drying can be done with outdoor air or with preheated air. In the first case the temperature of the ventilation air and the potatoes do not differ much. The air is only suitable for drying if there is a positive vapor-pressure deficit, that is, the vapor pressure in the ventilation air is lower than the equilibrium vapor pressure at the potato's outer surface. Generally this is reached when ventilation air temperature is equal to or slightly lower than potato temperature, and relative humidity of the ventilation air is lower than 92% to 95%.

In the case of drying with preheated air, ventilation air temperature is considerably higher than potato temperature, mostly as a result of preheating. There is only a drying effect if there is a positive vapor-pressure deficit, so relative humidity of the drying air

should be relatively low. When ventilation is done with this warm air, the ventilation air will cool. The energy set free is used to speed up the evaporation process. Remaining energy heats the potato bulk. When ventilation air cools below dewpoint, condensation in the potato stack results. This should be prevented.

Suberization or Wound Healing (Curing)

Potato tubers are subject to different degrees of damage during harvest, lifting, transport, transfer and storage, which can result in black spots and other quality losses. Moisture loss and liability to parasitic attack of wounded tubers is by far greater in comparison with undamaged tubers. The capability and recovery time of an injured potato to heal depends on variety, maturity of tuber, physiological state, and storage conditions. Influencing storage conditions can be identified as temperature, relative humidity, presence of sprout inhibitors, and O₂ and CO₂ concentrations. Wound healing is more rapid at higher temperatures. Wound-induced suberization and periderm formation occur most rapidly at 25°C and stop at a temperature of 35°C or temperatures below 5°C. Also, a higher relative humidity speeds up wound healing; however, condensation on the tubers or dry outer cell layers in the periderm slows down wound healing. Wound healing does not occur under anaerobic conditions, or more precisely at oxygen concentrations below 3% to 5%. High carbon-dioxide concentrations (5% to 15%) inhibit periderm formation also if oxygen concentrations are higher than 21% minus the CO₂ concentration (expressed as a volume percentage). Sprout-inhibitor application should be delayed to ensure formation of continuous wound periderm. If relative humidity is 80% to 95% and oxygen concentrations as close to 21% as possible and carbon-dioxide concentrations under 5%, the progress of the suberization process is measurable by counting degree days. Reference [10] gives a standard of 150 degree days to complete the process. The degree days are calculated as:

$$\sum_{i=1}^n (T_{\text{potato}} - 5) \geq 150 \quad (2.37)$$

where T_{potato} is the average potato temperature in the bulk. Potato temperatures higher than 20°C should be prevented. If the potato bulk shows severe damage, the required number of degree days can be increased. A numeric relation between degree of damage and required degree days is not available.

Cooling Down to Storage Temperature

Potatoes must be cooled to storage temperature. Both stored heat in the bulk (3600 J·kg⁻¹K⁻¹) and respiration heat (1000–4200 J·kg⁻¹d⁻¹ [11]) must be removed. In this phase the largest cooling capacity is needed to allow a fast decrease of temperature. Dependent on external climate, this can be achieved with outdoor air, optionally in combination with fixed or mobile mechanical cooling installations. In hot climates the use of cooling systems is inevitable. Cooling air with low enthalpy has the highest cooling capacity; however, a low humidity results in unacceptable moisture loss. Vapor deficit between potato and ventilation air should be limited or a lower limit to relative humidity of the ventilation air should be set (controller function). For example, 60%.

The ratio between heat loss and moisture loss can serve as an index number to guide this process:

$$\frac{Q}{M} = \frac{\alpha}{G_v} \frac{\partial T}{\partial C} + r \quad (2.38)$$

where

Q = heat loss per cubic meter [$\text{W}\cdot\text{m}^{-3}$]

M = moisture loss per cubic meter [$\text{kg}\cdot\text{s}^{-1}\text{m}^{-3}$]

∂T = local temperature difference between potato and ventilation air [K]

∂C = local absolute humidity difference between potato and ventilation air [$\text{kg}\cdot\text{m}^{-3}$]

r = evaporation heat of water [$\text{J}\cdot\text{kg}^{-1}$]

The heat-transfer coefficient (α) and moisture transfer coefficient ($G_v = \delta/r$; δ is described in Eq. (2.47)) are dependent on the ventilation rate. At airflow rates used in practice for mechanically ventilated stores, ventilation flows are approximately constant for given stacks and fans in operations. The ratio between energy loss and moisture loss (Q/M) then only depends on $\partial T/\partial C$. Strong temperature variation in the stack should be avoided to keep the potatoes dormant.

Long-term Storage or Holding Period

During storage, weight and quality loss should be minimized. Storage losses are determined mainly by potato condition, storage conditions, and duration of the storage period. Weight losses are caused by

- Respiration
- Evaporation of inter- or intracellular moisture from the potato
- Sprouting
- Storage diseases

By means of respiration the potato releases the required energy for its life processes. The respiration process converts carbohydrates (and oxygen) into carbonic acid, water and energy ($2825 \text{ kJ}\cdot\text{mol}^{-1}$ carbohydrates). The carbohydrates result from perpetual conversions of starch, which is a reversible chemical reaction controlled by enzymes and temperature. Respiration is minimal at 5°C , slowly increases until 15°C , and has a stronger increase at higher temperatures. Below 3°C respiration increases to be equal to that at 20°C at the freezing point. Respiration results in loss of dry matter, although these losses in well-designed stores seldom exceed 1.5% of the original fresh weight; however, this represents about 6% of the total dry material [11]. Indirectly, respiration causes more weight loss due to moisture removal as an effect of ventilation that was necessary to remove respiration heat load. Advised storage temperatures are given in Table 2.7.

Respiration rate is a function of environmental factors such as storage temperature (Table 2.8), humidity, potato volatiles, sprout inhibitors, and carbon dioxide and oxygen concentrations of the air. High humidity and sprout inhibitors decrease respiration rate. Figures on respiration rate are given in terms of heat production ($\text{W}\cdot\text{m}^{-3}$, $\text{W}\cdot\text{metricton}^{-1}$, or $\text{kJ}\cdot\text{metricton}^{-1}\text{d}^{-1}$) or in terms of carbon-dioxide production (1 mole per 470.8 kJ). Literature shows considerable variation concerning respiration heat production [13, 14].

**Table 2.7. Advised storage temperatures for potatoes
(in degrees Celcius)**

Potato Destination	Storage Temperature
Seed potatoes	2–4
Consumer potatoes	4–5
French fry\dried products	5–8
Chip industry	7–10
Starch and derivatives	6

Source: [12].

Table 2.8. Respiration heat production of stored potatoes

	4°C	6°C	8°C	10°C	14°C	20°C
Respiration heat ($W \cdot ton^{-1}$)	18	19	21	22	25	31

Source: [14].

Respiration of a sprouting potato is about four times as high as that of a dormant potato. Sprouts also significantly increase evaporation of moisture from the potato. Sprouting can be prevented at a storage temperature of 2 to 4°C or by applying sprout inhibitor. The generally used sprout inhibitor chemical is CIPC (isopropyl-N-[3-chlorophenyl]carbonate). This chemical controls the sprouting of consumer and processing potatoes which normally occurs 2 to 3 months after harvest. The duration of the dormancy period is strongly influenced by the storage temperature level and variations. CIPC is volatilized and distributed through the ventilation system after suberization and cool-down have been completed. It is not advisable to use the same store subsequently for seed potatoes as well, but if this is the case, all exposed structural surfaces and air contact surfaces should be thoroughly steam-cleaned.

Quality losses during this period are caused by

- Evaporation of water
- Change in the chemical composition
- Spreading of disease
- Damage from extreme temperatures

Product quality is greatly influenced by the history of the potato lot prior to storage. Quality is discussed further in Section 2.2.11).

Heating Up

Before delivery potatoes are heated, because at relatively low temperatures they are susceptible to black spot when handled. Dependent on the sensitivity of the variety, the temperature should be raised to 12 to 20°C (low-risk temperature range) or better to 15 to 18°C (safe temperature range). Temperatures over 20°C should be avoided to prevent black hearts. Heating can be done with the existing ventilation system, outside air or in colder climates gas or diesel heaters.

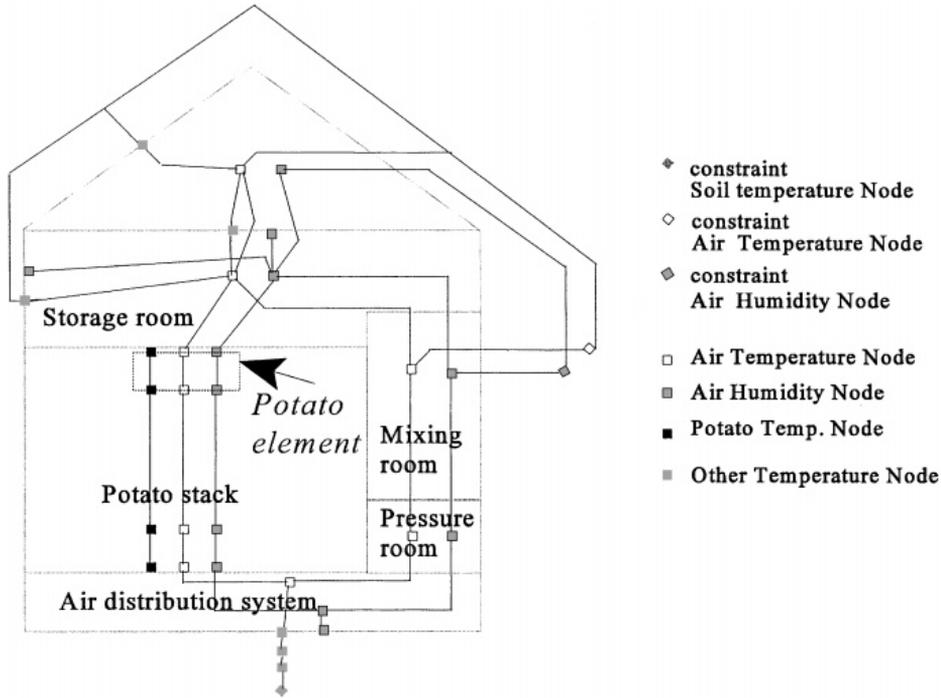


Figure 2.18. Division of potato stack and store in finite elements. (Source: [15])

Reconditioning

A considerable sugar accumulation, also called *sweetening*, occurs in tubers stored below 7°C. Reconditioning for several weeks at a temperature of 18 to 20°C can reduce the sugar content. This is especially important for industrially processed potatoes and chip potatoes in particular. Reconditioning can improve the baking quality, which is indicated by the color index number (discussed in Section 2.2.11).

2.2.7 Physical-Transport Phenomena in Potato Stack

In order to describe the temperature and moisture conduct of potato stacks, all transport processes within stack and storage room must be expressed in distributed dynamic balance equations. The potato stack can be divided into finite elements that describe nodes for potato temperature, air temperature, air humidity (Fig. 2.18).

For each node an energy or moisture balance is generated, using a finite-element method. An energy balance gives the energy storage in a node point as the sum of the heat production and the heat gains minus the heat sinks (both latent and sensible).

Three balance equations for each potato element are needed:

1. Heat balance of the potatoes:

$$\alpha_1 \frac{\partial T_p}{\partial t} = \alpha_2 \frac{\partial^2 T_p}{\partial x^2} + \alpha_3 T_a - (\alpha_3 + \delta\alpha_6 - \alpha_7) T_p + (\gamma - \beta\delta) + \delta C_a \quad (2.39)$$

2. Heat balance for air inside potato stack:

$$\frac{\alpha_4}{\alpha_3} \frac{\partial T_1}{\partial x} = T_a - T_1 \quad (2.40)$$

3. Moisture balance for air inside a potato stack:

$$\frac{\alpha_5}{\delta} \frac{\partial C_a}{\partial x} = (\alpha_6 T_p + \beta) - C_a \quad (2.41)$$

where

T_p = potato temperature ($^{\circ}\text{C}$)

T_a = air temperature ($^{\circ}\text{C}$)

C_a = vapor concentration in air ($\text{kg}\cdot\text{m}^{-3}$)

β = intercept of linearized C_{max} (ms^{-1})

$C_{\text{max}} = C_a$ at saturation (ms^{-1})

$\delta = r \cdot G_v$ ($\text{J}^2 \text{kg}^{-2} \text{s}^{-1}$)

r = evaporation heat of water ($\text{J}\cdot\text{kg}^{-1}$)

G_v = flow variable for mass transfer of vapor from potatoes to ambient air
($\text{J}\cdot\text{s}^{-1} \text{kg}^{-1}$)

γ = intercept of linearized potato heat production ($\text{J}\cdot\text{m}^{-3} \text{s}$)

The parameters used in the balance equations α_1 through α_7 , β , and δ are described below:

$$\alpha_1 = (1 - \epsilon)(\rho C)_p \quad (\text{Jm}^{-3}\text{K}^{-1})$$

where

ϵ = porosity of the potato stack

ρ_p = density of the potatoes ($\text{kg}\cdot\text{m}^{-3}$)

C_p = heat capacity of potatoes ($\text{J}\cdot\text{kg}^{-1} \text{K}^{-1}$)

The porosity of potatoes in storage is independent of the size and shape of the potatoes. If they are assumed to be bulb-shaped with equal diameter, this is called the equivalent potato diameter. The porosity of stacked equal-sized bulbs is 0.26 [16]. Potatoes are not exactly bulb-shaped, nor do they have an equal hydraulic diameter. This leads to a higher porosity. Boel estimated for the porosity of potato stacks a range of 0.33 to 0.36. The density of potatoes is dependent on the circumstances during growth. Potato density is about $1080 \text{ kg}\cdot\text{m}^{-3}$ and heat capacity of potatoes is about $3560 \text{ J}\cdot\text{kg}^{-1} \text{K}^{-1}$.

$$\alpha_2 = \lambda_v$$

$$\lambda_v = \text{apparent heat conductance} \quad (\text{W}\cdot\text{m}^{-1} \text{K}^{-1})$$

The value for the heat conductance is according to Hendrikse [17] equal to 0.33.

$$\alpha_3 = \alpha A_v$$

where

α = heat-transfer coefficient ($\text{W}\cdot\text{m}^{-2} \text{K}^{-1}$)

A_v = potato surface area per cubic meter ($\text{m}^2 \text{m}^{-3}$)

Ample research has been done on estimation of the value of this heat-transfer coefficient at different ventilation rates and different sizes and shapes of the potato stack. The results

are given in a form in which the Nusselt number (Nu) is presented as a function of the Reynolds number (Re) and Prandtl number (Pr). Beukema [18] gives this function for Re greater than 180:

$$Nu = 1.27(1 - \epsilon)^{0.41} Re^{0.59} Pr^{0.33} \quad (2.42)$$

where

v = air velocity in potato stack ($=1/\epsilon * v_{undisturbed}$) ($m \cdot s^{-1}$)

ν = viscosity of air ($=1.4 * 10^{-5}$) ($m^2 \cdot s^{-1}$)

d = average potato diameter (m)

λ = heat conductance air ($=0.021$) ($W \cdot m^{-1} K^{-1}$)

From the heat transfer coefficient for *Regreaterthan*180 can be derived:

$$\alpha = \frac{\lambda}{d} 1.27(1 - \epsilon)^{0.41} \left(\frac{dv}{\nu}\right)^{0.59} \left(\frac{\nu}{d}\right)^{0.33} \quad (2.43)$$

The heat transfer coefficient is dependent on the air speed and can be described as a function of the air speed for $\epsilon = 0.33$ and $d = 0.05$:

$$\alpha = 3.80v^{0.59} (W \cdot m^{-2} K^{-1})$$

The surface area per cubic meter for bulbs can be described by the following equation:

$$A_v = \frac{6(1 - \epsilon)}{d} \quad (2.44)$$

Boel [16] indicates that this equation provides a good estimation for the area of potatoes.

A convection parameter for heat transport with air moving through the potato stack, dependent of the real air velocity in the potato stack (disturbed air velocity), is α_4 .

$$\alpha_4 = v_d * (\rho C)_a (J \cdot m^{-2} K^{-1} s^{-1})$$

where v_d is the disturbed air velocity in the potato stack ($m \cdot s^{-1}$). The parameter α_5 depends on the undisturbed air velocity:

$$\alpha_5 = \epsilon v_u (ms^{-1})$$

Equation (2.45) gives a linearized function for maximum moisture concentration in air, C_{max} ($kg \cdot m^{-3}$), using different α_6 and β values in several temperature intervals.

$$C_{max} = \alpha_6 T_p + \beta \quad (2.45)$$

The heat production of the potatoes in storage is estimated with the following linearized function.

$$Q_p = \alpha_7 T_p + \gamma \quad (2.46)$$

where

Q_p = heat production of potatoes ($W \cdot m^{-3}$)

γ = intercept linearized Q_p ($=3.4$) ($W \cdot m^{-3}$)

α_7 = trend in linearized Q_p ($=0.4$) ($W \cdot m^{-3} K^{-1}$)

The given values of α_7 and γ are only valid in the temperature range from 3 to 10°C.

Finally, the parameters δ and β are discussed. δ is split into two complementary parameters, one for evaporation from the inside of the potato and one for evaporation and condensation of water on the outer surface of the potato:

$$\delta = SW\delta_1 + |SW - 1|\delta_2 \quad (2.47)$$

where

δ_1 = energy flow needed to evaporate 1 kg of water from the inside of the potato ($\text{W}\cdot\text{kg}^{-1}$)

δ_2 = energy flow needed to evaporate 1 kg of water from the potato's outer surface ($\text{W}\cdot\text{kg}^{-1}$)

If condensation on the potatoes occurs the switch function $SW = 0$; in case of normal evaporation through the potato peel, $SW = 1$.

δ_1 can be described as:

$$\delta_1 = rA_v\gamma\left(\frac{1}{\beta} + \frac{r\delta}{D}\right)^{-1} \quad (2.48)$$

β = mass transfer coefficient from a wet surface to air ($\text{m}\cdot\text{s}^{-1}$)

where

$r\delta$ = depth of the potato peel (m)

γ = permeability of the potato peel

r = evaporation heat of water ($=24.85 \times 10^5$) ($\text{J}\cdot\text{kg}^{-1}$)

D = diffusion coefficient of vapor in air ($\text{m}^2\text{ s}^{-1}$)

The mass transfer coefficient β ($\text{m}\cdot\text{s}^{-1}$) in this equation is equal to [18]:

$$\beta = \frac{\alpha}{\rho C} Le^{-\frac{2}{3}} \quad (2.49)$$

where

Le = the Lewis number, a/D

a = heat distribution coefficient of air ($\text{m}^2\text{ s}^{-1}$)

The equation describing the heatflow per kilogram of condensed water (δ_2 [W kg^{-1}]) is:

$$\delta_2 = rA_v\beta \quad (2.50)$$

The three basic equations (2.39) through (2.41) can be used to create element matrices in order to allow computational calculation of a matrix-vector equation set: $M^e \dot{\underline{T}}^e + S^e \underline{T}^e = \underline{f}^e$ for each element defined. The element mass matrix M^e is multiplied with the derivative of the element state vector $\dot{\underline{T}}^e$, added to the element-stiffness matrix S^e multiplied with the element state vector \underline{T}^e , which equals the element loads vector \underline{f}^e . The state vector holds the state variables: potato temperatures, air temperatures, and air humidities; the loads vector \underline{f} contains all state variable independent parts of the balance equations. This set of equations can be completed by adding elements for ventilation, heat loss through the construction of the storage (see Fig. 2.18), and

heat flows to and from equipment such as heaters, coolers, fans, and humidifiers. All element matrix equations can be aggregated into one matrix equation describing the total potato storage system: $M\dot{T} + ST = f$. This equation can be the core of a model description of a potato store. An example of such a model is AMOD [15], which is developed by Wageningen Agricultural University in cooperation with Delft Technical University.

2.2.8 Process Control

In controlling the storage process we distinguish different ways to manage actuators like fans, mixing valves, and air-conditioning units such as coolers, heaters, humidifiers, and anticondensation units:

- Manual control: cheap but inaccurate. Disadvantages are that a lot of human attention to the control process is required, the chance of unwanted effects, and that it is not an optimal use of available time if ventilation with outdoor air is appropriate.
- Minimum/maximum control using thermostats: This control is only effective if potatoes are cooled down. The maximum thermostat setting is approximately 2°C below the product temperature and the minimum thermostat setting is about 4°C below the maximum but never below 1 to 2°C. If outdoor air temperature is between the setpoints of the two thermostats, ventilation air is allowed in to cool the stack.
- Differential control using thermostats: This control uses the product temperature, outdoor temperature, and temperature in the air-distribution system as inputs. Fans are turned on if the product temperature is outside the setpoint area and the preset temperature difference between outdoor air and the product is a fact. The mixing valve is controlled with help of the measured temperature in the air-distribution system. A disadvantage is that control of humidity and of air-conditioning units requires separate control units.
- Control with process computer: Indoor climate and potato temperature are controlled automatically based on a chosen or given control strategy, which can be different for each phase in the storage process, based on product temperature and on temperature and humidity of outdoor air, air in the storage room, and air in the air distribution system. Advantages are a full integration of the control of all actuators; that ventilation with outside air, mixed air, and conditioned air can be controlled by the process computer based upon economic criteria; that no additional equipment such as timers is needed (for periodical internal ventilation, use of cheaper power rates, etc.); and that the process computer can be coupled with a personal computer to allow remote monitoring and control of setpoints and postprocessing of data.

2.2.9 Equipment in Storage Houses

The most important equipment in a potato store is the airflow equipment (fans) plus the air-distribution system (which is part of store construction), mixing valves, air-conditioning equipment, and sensors.

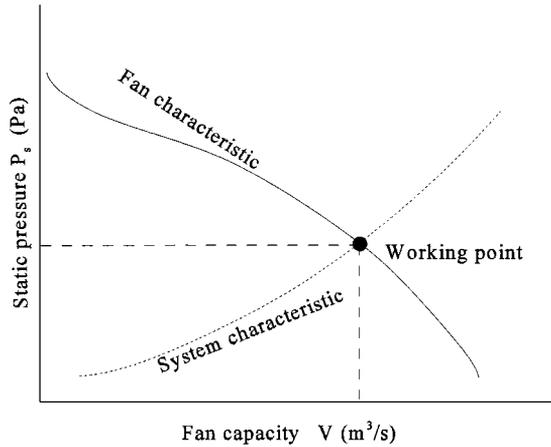


Figure 2.19. Working point of a fan.

Airflow Equipment

Fan Types

The fan capacity strongly influences both the cooling and drying rates in the store and therefore cannot be chosen arbitrarily. It must be chosen on the basis of the required cooling and drying rates. To be able to dry and cool potato lots a ventilation rate of 100 to 150 $\text{m}^3 \text{m}^{-3} \text{h}^{-1}$ is required. This rate is dependent on the external climate and the cooling rate required in the cool-down period. The airflow generated by a fan is dependent on the static pressure head in the system. Generally, large axial-flow fans are used, which generate airflows of 30,000 to 50,000 $\text{m}^3 \text{h}^{-1}$ at a 200-Pa static pressure difference. In the choice of a fan type not only airflow is important, but also the stability of the working point (Fig. 2.19), the ventilation efficiency ratio ($\text{m}^3 \text{s}^{-1} \text{kW}^{-1}$) or specific power consumption (W per 1000 $\text{m}^3 \text{h}^{-1}$), noise production, and durability of the fan as a whole.

Working Point of a Fan

As discussed previously there are resistances that act against the air flowing in the whole storage system. To realize the desired air flow, the fan must build a pressure head that is equal to the static pressure losses due to these resistances. The working point of a fan is defined by the point at which the fan and the system characteristic (system resistance) meet (see Fig. 2.19).

The fan characteristic can be described by the following equation:

$$P_s = a + b\left(\frac{V}{n}\right) + c\left(\frac{V}{n}\right)^2 + d\left(\frac{V}{n}\right)^3 + e\left(\frac{V}{n}\right)^4 + f\left(\frac{V}{n}\right)^5 \dots \quad (2.51)$$

where

P_s = static pressure generated by fan (Pa)

n = number of fans

V = total fan capacity of the potato storage ($\text{m}^3 \text{s}^{-1}$)

a..f. = fan type-specific numeric parameters

Equation (2.51) allows the option to install more than one fan in the store. The generated static pressure will remain constant, but the airflow will increase proportionally with the number of fans at the given static pressure. The fan working point can be calculated by finding the airflow rate at which the fan generates a static pressure head that is equal to the system pressure head (Eqs. (2.51) and (2.62)). With the help of iteration the airflow rate through the system can be calculated.

Natural Ventilation

Natural ventilation is the result of stack effect, is wind-induced, or results from the combined effect of these two forces. Natural ventilation is induced as a result of temperature difference between inside and outside environment and height difference between the inlet and outlet vents in a naturally ventilated structure (stack effect). Wind-induced ventilation depends on the location of the building. It has been shown to contribute a lot in naturally ventilated structures. The following equations can be used to calculate the static pressure head generated by stack and wind effect.

Velocity of air due to thermal buoyancy (stack effect) is given by:

$$\Delta P_s = g \Delta h (\rho_o - \rho_i) \quad (2.52)$$

where

Δh = height difference between inlet and outlet opening (m)

ρ_o = density of outside air ($\text{kg}\cdot\text{m}^{-3}$)

ρ_i = density of inside air ($\text{kg}\cdot\text{m}^{-3}$)

g = acceleration of gravity ($\text{m}\cdot\text{s}^{-2}$)

The static pressure due to wind effect is given by

$$\Delta P_s = (C_i - C_o) \frac{1}{2} \rho_e V_w^2 \quad (2.53)$$

where

$C_{o,i}$ = outside and inside pressure coefficient

V_w = wind speed at meteorological reference height ($\text{m}\cdot\text{s}^{-1}$)

ρ_e = density of outside air ($\text{kg}\cdot\text{m}^{-3}$)

The possibilities of natural ventilation as a driving force for stack ventilation can be estimated in a simple way by replacing Eq. (2.51) with equations, describing the driving force for natural ventilation (Eqs. (2.52) and/or (2.53)). Natural ventilation can be important for small farms in locations in which means are lacking for a mechanical ventilation system.

Air Distribution System

The goal of air-distribution systems is an equal distribution of air over the inlet area of the stack. A properly designed air-distribution system reduces weight losses and temperature gradients in the stack, and sprout inhibitors are distributed better. A secondary requirement is that the air-distribution system may not form a large obstruction during loading and unloading of the store.

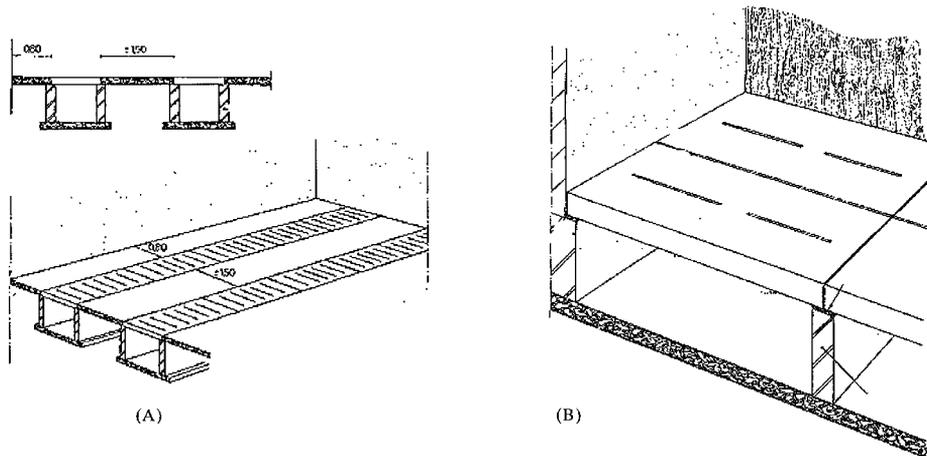


Figure 2.20. Underground channels (A) and fully slatted floor (B) under potatoes stored in bulk.

Potatoes Stored in Bulk

Practical systems are channels above floor level, channels below floor level, or fully slatted floor with aeration channels below (Fig. 2.20). A fully slatted floor is the best solution to achieve optimal air distribution, because there are no floor parts through which no air is admitted to the stack. Airspeed at the entrance of the floor channels should be 4 to 6 $\text{m}\cdot\text{s}^{-1}$.

Channels above floor level are wooden triangular ducts or perforated half-round corrugated steel elements. Low investment and high flexibility of floor use are the main advantages. The distance between the center line of two channels should be smaller than or equal to the stack height to prevent dead areas. Airspeed in the channels may range from 6 to 10 $\text{m}\cdot\text{s}^{-1}$. To restrict friction losses and allow good air distribution a maximum air speed of 8 $\text{m}\cdot\text{s}^{-1}$ should be considered. To allow uniform distribution of outlet airflows along the length of the duct, the cross-section must decrease with the length measured from the inlet side without showing sudden changes. Outlet openings must be projected as close to the floor as possible to prevent dead areas. For wooden channels the total outlet area of a duct may be two to three times the area of the cross-section of the largest element. For half-round steel ducts the outlet area should be restricted to 1.5 to 2 times the cross-sectional area of the largest element. The obstruction of outlet openings by potatoes is smaller with half-round corrugated steel pipes than with triangular wooden ducts. An airspeed of 4 $\text{m}\cdot\text{s}^{-1}$ in the outlet openings is seen as an optimum value that allows minimal pressure loss.

Underground channels are projected closer together. A center-line distance of two channels of 80% of the stack height is advised. Underground channels are designed as equal (static) pressure channels or as channels with a constant cross-sectional area. For equal-pressure channels the ratio of hydraulic diameter at the rear end and the hydraulic diameter at the front end should be between 1 : 4 and 1 : 6. The shape theoretically needed

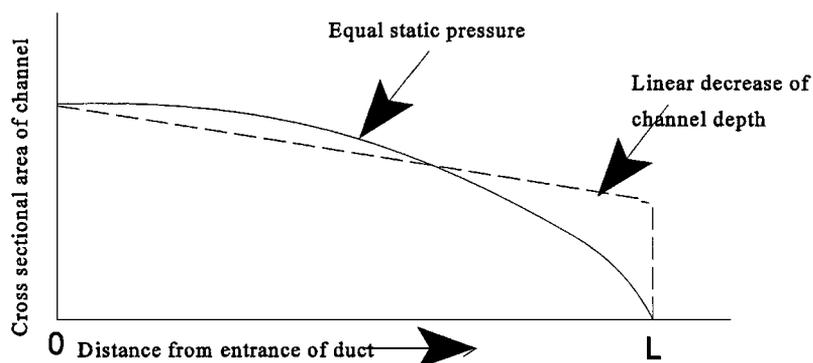


Figure 2.21. Floor shapes of channels for equal static pressure. (Source: [12])

to generate constant static pressure (Fig. 2.21) is hardly ever applied because of complex construction (high investment).

In practice, channels with a constant cross-section area are more common, because of the more simple construction (lower investment), and air distribution is quite good if the ratio of total outlet area to cross-section area is chosen right. Optimal air speed in the channels lays around $6 \text{ m}\cdot\text{s}^{-1}$ at the inlet of the channel. As a consequence of the obstruction by potatoes, total outlet area may be two to three times the cross-sectional area at the front end.

Storage in Crates

With aeration through the crates the aeration ducts are formed by the crates. Additionally a drying wall or ventilation wall with openings that connect to the crate-row openings with the pressurized room behind this wall is needed. The air is drawn in at the top side. The pressure room is designed as an equal (static) pressure room or as room with constant cross-sectional area (Fig. 2.22). In the latter case the lower crate rows get the highest amount of air. At the top rows the dynamic pressure head is still too high to allow good air admittance to the crates. This negative effect can be decreased by installing air conductor blades at the top rows. Leakage losses between the ventilation wall and crate openings and among crate connections are inevitable but should be minimized. Even with use of well-shaped crates these losses are about 20% of the total airflow. For aeration along crates Section 2.2.5 gives an adequate description of required distances between crates and between crates and walls.

System Flow Characteristic (Airflow Resistance)

The system resistance in the potato store consists of the following:

- Pressure drop at inlet openings
- Resistance in the air-distribution system (pressure head in the channel due to friction in the channel and transitions or outlet openings and 90-degree bends)
- Stack resistance
- Resistance at the outlet opening of the storage

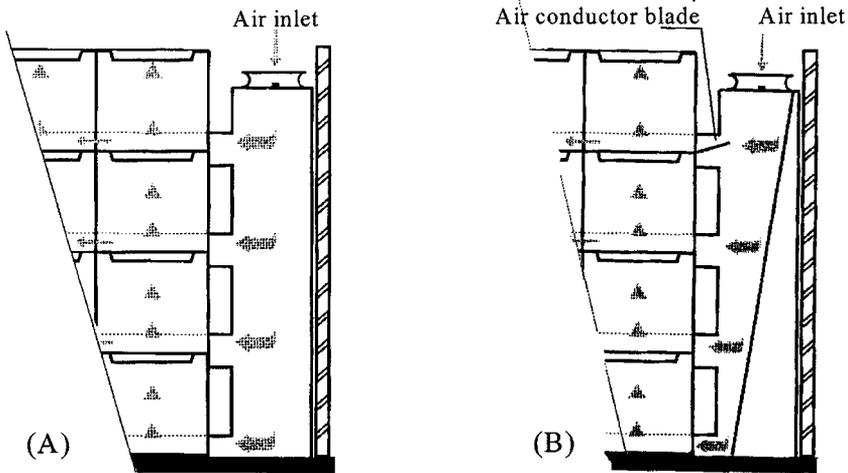


Figure 2.22. Different designs of pressurized rooms for crate storage: (A) constant sectional area; (B) equal pressure. (Source: [7])

Resistance at the Inlet Opening

The resistance at the inlet opening can be calculated by the following equation:

$$\Delta P = \frac{C_{\text{open}}}{(A_{\text{open}})^2} \frac{1}{2} \rho V^2 \quad (2.54)$$

where

C_{open} = resistance coefficient (Euler number) for a sharp rectangular opening

A_{open} = area of the inlet opening (m^2)

V = airflow through the opening ($\text{m}^3 \text{s}^{-1}$)

The air passes this opening before it passes the fan. The value of the Euler number for sharp openings is approximately 2.5, which is equivalent to a discharge coefficient of 0.63 [20].

Resistance in the Air-distribution System

While moving from the inlet opening to the potatoes the air encounters first the fan, then one or two 90-degree turns between the pressure room and the duct system below the potato bin. The first component of the resistance, generated by the 90-degree turn, can be calculated using the approach described for the inlet opening. Only the Euler number changes from the calculation for the inlet openings:

$$\Delta P = \frac{n C_{90^\circ}}{(A_{\text{duct}})^2} \frac{1}{2} \rho V^2 \quad (2.55)$$

where

C_{90° = resistance coefficient of a 90-degree curve

A_{duct} = area of the duct after passing the 90-degree curve (m^2)

N = number of 90-degree curves

The value of the resistance coefficient in this equation is 1.3 [21]. Because the calculation of resistance in the air-distribution system is iterative and intensive, it cannot be determined with this simple approach because several factors affect the pressure distribution. These factors are the duct design and the air velocity in the duct or the airflow rate through the duct. However, a simple approach is followed to calculate this resistance. The static and dynamic pressure distributions in the channel are calculated for the desired airflow rate, which is in itself a rather complex algorithm [22] which is not further discussed here but is part of the model. The ratio of the static and dynamic pressures at the entrance of the duct is equal to an effective airflow resistance coefficient (Euler number) that represents the pressure loss in the total air-distribution channel. Hence:

$$C_{\text{chann}} = \frac{P_s(1)}{P_d(1)} \quad (2.56)$$

where

C_{chann} = airflow resistance coefficient (Euler number)

$P_s(1)$ = static pressure head in the front end of the channel

$P_d(1)$ = dynamic pressure head in the front end of the channel

The static pressure head required to allow an airflow rate (V) through the air-distribution system, being a combination of 90-degree turns and the air-distributing channels, is given by the following equation:

$$P_s = (C_{\text{channel}} + nC_{90^\circ}) \frac{1}{2} \rho \left(\frac{V}{A_{\text{channel}}} \right)^2 \quad (2.57)$$

The value for the resistance coefficient of the channel may vary depending on the type of channel/duct and for different dimensions of channel/ducts. Important factors are the number of gap stations, cross-sectional area, friction factor of the channel's wall, and the coefficient for static pressure gain. A gap station is a location along the length of the channel at which one or more discharge gaps can be found in the channel. The calculated distribution of dynamic and static pressure allow detail evaluation of the duct design. See Inlet and Outlet Area Calculation for the Air Distribution System (page 117).

Ducts are designed either for equal static pressure or for constant cross-sectional area. For constant static pressure through the length of the duct, the area of the cross-section will decrease towards the far end of the duct. In case of constant cross-section of channels, the shape of the cross-section does not change. For rectangular channels with linear decrease to the depth, the following equation can be used to calculate the cross-sectional area of the duct as a function of the position in the channel:

$$A(I) = WD \left(1 - \frac{I-1}{N-1} (1-T) \right) \quad (2.58)$$

where

$A(I)$ = cross-sectional area at the gap station I (m^2)

W = width of the channel (m)

D = duct or channel depth at the inlet (m)

I = counter (1, ..., N)

N = total number of gap stations in the channel

T = ratio of the cross-section area in the rear end and the front end of the channel.

In the case of half-round corrugated steel ducts the cross-section area can be calculated from:

$$A(I) = 0.5\pi \left(H \left(1 - \frac{I-1}{N-1} (1 - \sqrt{T}) \right) \right)^2 \quad (2.59)$$

where H is the height of the duct at the front end (m^2).

A proper description of calculations needed to quantify C_{chann} is given by ref. [22].

Resistance in the Stack

Ergun, according to Beukema [18], developed the following equation to calculate pressure drop in packed beds of spherical particles:

$$\frac{\Delta P}{L} = \frac{1 - \varepsilon}{d_p \varepsilon^3} \left(\frac{150(1 - \varepsilon)}{Re} + 1.75 \right) \rho V^2 \quad (2.60)$$

$$Re = \frac{\rho v d_p}{\mu}$$

where

ΔP = pressure drop in potato stack ($\text{N} \cdot \text{m}^{-2}$)

Re = Reynolds number

ρ = air density ($\text{kg} \cdot \text{m}^{-3}$)

V = velocity in the stack ($\text{m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)

ε = porosity of the material (potato)

μ = viscosity ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$)

L = length of stack in flow direction (m)

d_p = equivalent diameter of a potato in the stack (m)

In research by Bakker-Arkema *et al.* [23, 24], the Ergun equation was compared with experiments on biological products. Another more experimental equation to describe the stack resistance is [12, 25]:

$$\Delta P = K V^{1.8} L \quad (2.61)$$

The K value, an empirical constant, depends on potato size distribution, shape and the amount of soil tare included in the potato lot. It varies from 500 to 1500 for 0% to 10% soil tare [25]. Figure 2.23 compares the result of Eqs. (2.60) and (2.61).

Total System Resistance

Bringing together all the components of the system resistance results in total static pressure loss in the system. This is given by the following equation:

$$P_s = \frac{1}{2} C_o \left(\frac{V}{A_0} \right)^2 + \frac{1}{2} (C_{\text{ch}} + n C_{90^\circ}) \dots \left(\frac{V}{A_{\text{ch}} N_{\text{ch}}} \right)^2 + K V^{1.8} L \quad (2.62)$$

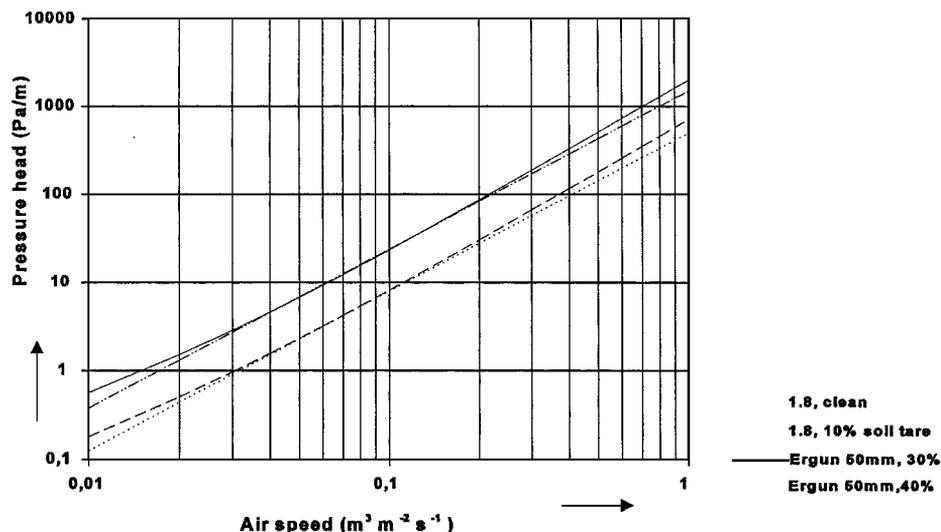


Figure 2.23. Pressure loss in a potato stack for clean and soiled potatoes according to Ergun — equation (2.60) and to the experimental equation (2.61).

with subscripts:

o = opening

ch = channel

N_{ch} = number of channels in the system

Inlet and Outlet Area Calculation for the ADS

The static pressure distribution is sensitive to the aperture ratio (total duct outlet area divided by duct inlet area, A_o/A_i) as discussed in Air Distribution System in this section. Increasing this ratio magnifies the static pressure variation in ducts [26], which in turn affects the uniform distribution of air flow in the stack. They also recommend for different duct types an effective aperture ratio of in general less than 1. It is found that in stores only 25 to 50% of the opening is available for air flow through the stack, the rest is covered by the potatoes (Fig. 2.24), so the gross ratio can be higher. Cloud and Morey [27] suggest a value of two for this aperture ratio.

Figures 2.25 and 2.26 show two examples: I) the air output distribution along an underground channel as a function of the aperture ratio (A_o/A_i) and II) the air output distribution along differently designed equal pressure corrugated steel ducts as a function of the parameter (T).

Air-conditioning Equipment

Heaters

Heaters are used when the product temperature should rise considerably in a relative short period of time in order to sort or deliver and/or recondition a potato batch. The use

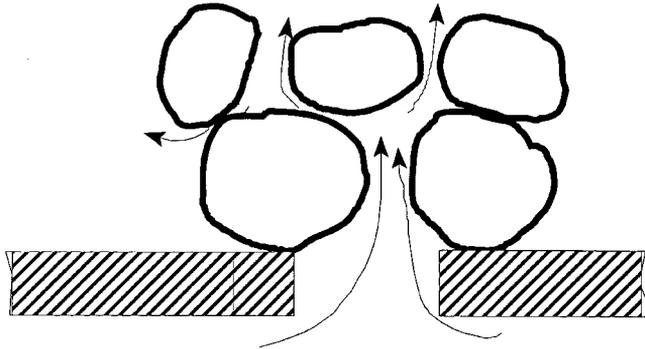


Figure 2.24. Potatoes covering 50% to 75% of the outlet opening.

of warm outdoor air is not advisable because of its high humidity. When the potatoes are still below dewpoint of the air considerable condensation can take place. By heating colder air with a low humidity condensation is prevented. Evaporation however will increase. Heaters are normally projected in the mixing room or pressure room (see Fig. 2.18). Three different fuels for heating units can be used: electricity, diesel fuel, and natural gas. Diesel heaters can only be controlled with on/off control. Natural gas burners can be controlled with on/off and linear control in the range of 40% to 100%. There are diesel and gas heaters that heat the ventilation air indirectly with the help of a transport medium. The advantage is that no exhaust gases are brought into the potato stack, and no oxygen is consumed nor is carbon dioxide produced. This means that no extra ventilation with external air is needed to correct the gas concentrations. Indirect heaters have lower energy efficiencies than direct heating systems. Electrical heaters are not advised because of the high energy costs.

Cooling Unit

A cooling unit allows a longer storage season and guarantees an adequate reaction if cooling is required and outdoor air or mixed air cannot be brought in the required condition. In the cool-down period a cooling unit can help realize a steady decrease of the potato temperature, while outdoor air can show longer time periods in which cooling is not possible. A cooling unit is mostly used in combination with cooling with outdoor air to keep costs down. The control algorithm is responsible for a proper use of both cooling mechanisms.

Humidifiers

Sometimes humidifiers are used to prevent weight loss if the normal ventilation air is too dry. Two main ways of humidifying air are available: evaporation of water from a large wet surface or spraying of water in the ventilation air with high-pressure nozzles to minimize droplet size. If spraying is applied, the amount of water added to the air must be controlled in order to allow full evaporation before the ventilation air reaches the potatoes. Evaporation from a wet surface normally is realized by leading the air

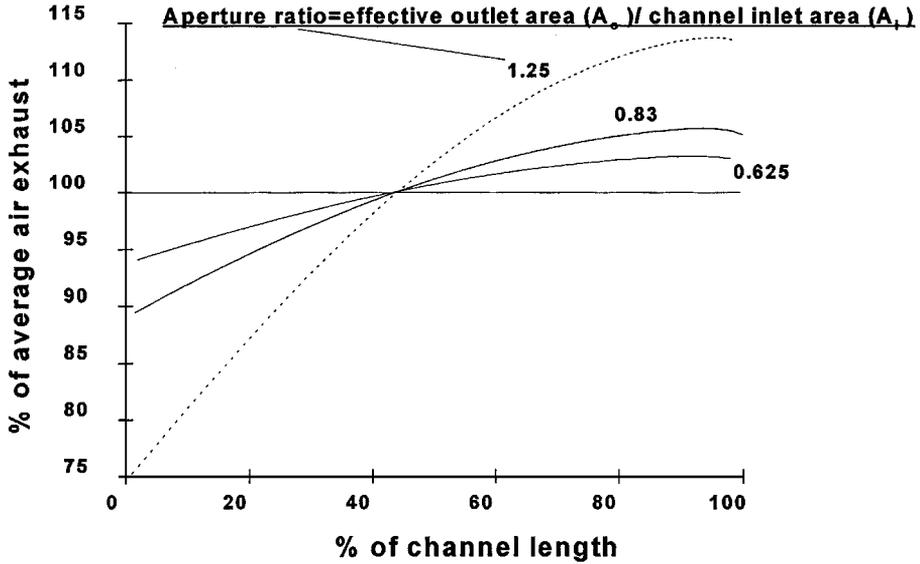


Figure 2.25. Calculated air output distribution along the length of an underground ventilation channel for different aperture ratios: 0.625, 0.80, and 1.25. Channel dimensions: $L \times W \times H = 10 \text{ m} \times 1 \text{ m} \times 0.8 \text{ m}$.

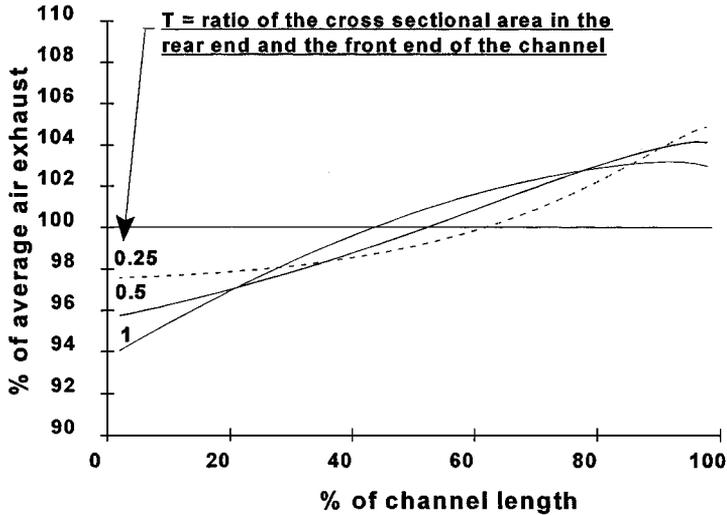


Figure 2.26. Calculated air output distribution along the length of corrugated steel duct for different ratios between the cross sectional area at the front and rear end. Dimensions of duct: 10 m long, height at front end 1 m.

through a wet pad. This humidification process is almost adiabatical; that is, enthalpy of the ventilation air is approximately constant. This means latent heat is added and an equal quantity of sensible heat is removed. The consequence is that the humidified air cools down.

Anticondensation

Equipment to prevent condensation in the storage room is restricted to additional small fans in the room between potato stack and ceiling (see Fig. 2.17) or in the end walls of the storage room above the highest potato level to refresh the air in the storage room (see Section 2.2.5).

Sensors

In order to get information from the storage process, or the indoor climate, temperature and humidity measurements have to be carried out. Common temperature sensors in automatically controlled stores are PT-100 and NTC sensors, in which the electrical resistance is temperature-dependent. The NTC has a high resistance, thus making the cable resistance negligible, but sensors of different producers cannot be exchanged and the sensors are not entirely stable. After long-term usage the accuracy decreases. The PT-100 sensor is most common. The sensor is very stable and exchangeable with other brands. Because of the low electrical resistance, correction for the cable resistance is necessary. For this purpose a more expensive three- or four-wire cable is necessary. A standard PT-100 element has an inaccuracy of 0.3°C. More accurate sensors are available but more expensive. On average, one temperature sensor per 100 ton of potatoes is enough. Further, it is advisable to place some sensors near the sidewalls of stores to monitor extreme temperatures in the stack. Sensors with different pen lengths are available to allow temperature measurement at various levels in a potato stack. To prevent errors from electrical or magnetical fields the use of shielded cables is advisable. Relative-humidity sensors are normally capacitive sensors.

2.2.10 Product Handling During Storage

Loading of Bulk Stores

A field transport load is received in a buffer unit that should produce a constant, clean product flow to the transport belts. Best is if the product flow is measured and the speed of the floor belt is adjusted accordingly. The second function is to clean soil tare from the potatoes. Then the product is put on a transport line, consisting of low speed V-shaped transport belts with a transport capacity of about 70 ton/h. At the end of the transport line a special-purpose transport belt is used, a “cell loader,” which can move up and down to restrict the falling height and which moves along a circle segment of varying radius to allow equal loading over a full cell width. Some times the movements of cell loaders can be programmed to allow automatic terrace filling [25]. Drop heights of potatoes should be restricted to less than 150 mm for a free fall on a hard surface, less than 300 mm for a fall on other potatoes, and less than 750 mm if the fall is broken on a soft 45 degree-angled surface. The allowable drop height is somewhat dependent on the potato’s diameter. Large diameters require a smaller maximum fall height.

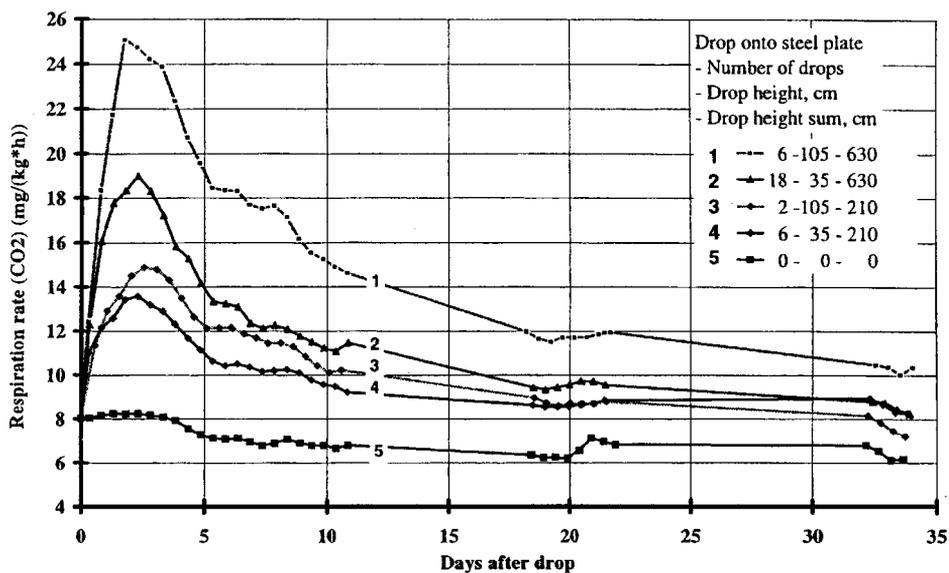


Figure 2.27. Effects of mechanical damage on respiration rate of onions.

Points of attention during loading of a store are to work with clean machinery and to check and correct the running of transport belts and scrapers.

Loading Crate Stores

Crate stores are loaded using crate-fill equipment and fork-lift trucks for transport and placement in the store. It is important not to put too much force on a ventilation wall in the process of loading.

Other Product Handling

Other product handling during storage is unloading and sorting. These processes are not discussed here.

2.2.11 Product Quality-Inspection Systems

Quality is determined not only by storage conditions but also by the history prior to storage. Division of the bulk in healthy batches and risk batches in combination with crate storage and precision farming could be a promising future challenge for better potato quality.

The quality and the size distribution of a bulk of potatoes determine price and possible market outlets. Size distribution can be influenced by sorting potatoes. Quality has many aspects. In most countries different quality-inspection regulations are prescribed for different product destinations, such as fresh consumption and industrial processing, sorted potatoes for french fries, potatoes for potato-chip manufacturing, potatoes for mashing and granulation, and potatoes destined for dried products.

Table 2.9. Possible defects in potatoes

Defect Permitted Percentage	
Frost damage	0
Attached soil (tare)	2
Decay (wet rot)	2
Black hearts	2
Glass	3
Powder burn	3
Internal sprouts > 1 cm	3
Scabies	3
Wrinkling or limpness	5
Physical defects and growth cracks	8

Generally, from a potato lot, two samples are taken for inspection, one for the inspection at hand and the other for a second opinion if requested by the grower. The samples are generally assessed on:

- Weight percentage of tare (soil and sprouts) and weight percentage of potatoes with defects (Table 2.9)
- Distribution of potatoes over a range of sorting classes
- Quality index based upon black coloring, internal coloring, and glassiness
- Temperature at arrival ($\geq 12^{\circ}\text{C}$), underwater weight, baking color index

Frost damage can occur due to an error in the ventilation system or due to an insufficient insulation level. Rot can be caused by wet potatoes, glass, poor ventilation, or condensation on walls or ceiling. Black hearts are caused by an oxygen deficit in the tuber. Heating up potatoes with air that is too warm increases dissimilation, which can cause a shortage of oxygen [12].

Powder burn shows as thick and leathery peel at places that were damaged previously. The use of chemical means for sprout control on damaged tubers induces powder burn, especially in combination with incomplete wound healing. Spots larger than 20 mm are seen as external defects [29]. Internal sprouting occurs if time intervals between administering sprout suppressants are too long. We speak of scabies on a tuber if more than one sixth of the tuber surface shows this disease and the depth of the damaged area is more than 2 mm. At a moisture loss higher than 10%, wrinkling and limpness occurs. Tubers with growth cracks longer than one third of the tuber length and depths larger than 10 mm are rejected. The distribution of a potato batch over sorting classes influences the price greatly. Larger sizes and more uniform lots get a better price. Based on the quality index a bonus or rebate is calculated over the yield price. A poor quality index can even cause rejection of a potato lot by a buyer (wholesaler or in the processing industry).

Sensitivity for black spots can be measured by shacking a sample for 30 seconds, which is considered normal in practice. Then the potato sample is preserved for 48 hours to allow black coloring. Black spots occur if potatoes are not heated properly before transport. After peeling the sample, the tubers are divided in four classes based on the largest black spot: I) no black spots, II) light (spots < 2 mm), III) moderate (diameter between 2 and 5 mm), IV) heavy (diameter black spots > 10 mm).

Glassiness is judged by submerging a sample in a salt bath. The density of the salt water is variety-dependent. Floating potatoes are cut to show the largest cut area and assigned to three classes of glassiness (light, moderate, heavy).

The underwater weight is a measure for the dry-matter content of potatoes, and it is measured by submerging 1000 g of potatoes in a water vessel. The minimum value for the underwater weight is 360 g. The dry-matter content can be calculated from [8]:

$$\% \text{ dry matter} = 0.0492 \cdot \text{underwater weight} + 2.00 \quad (2.63)$$

For french fries and the potato-chip industry baking quality is important. Dependent on the concentration of reducing sugars during a baking process, the product can show a dark color and a bitter taste. The test on reducing sugar is carried out by selecting 20 healthy tubers, cutting one fry of 1×1 cm from each tuber, baking the fries, and judging, the color against a standard color-index chart. This results in a baking color index that may not be higher than 4, which is equivalent to 0.35% reducing sugars in the fresh weight of the potatoes.

The potato storage process can influence these quality parameters: black spots, baking color index, decay, frost damage, black hearts, powder burn, internal sprouting, and moisture loss (wrinkling and limpness).

References

1. Britannica CD version 2.0, Encyclopaedia Britannica 1995.
2. Britannica World Data. 1997. *Britannica Book of the Year*. ed. D. Calhoun. Encyclopaedia Britannica, Chicago.
3. LEI-DLO. 1994. Landbouwcijfers [Dutch Agricultural Statistics]. The Hague. NIVAA, The Hague Netherlands.
4. NIVAA Holland. 1995. Productie en afzet consumptie- en industrieaardappelen [Production and market for consumer and processing potatoes]. The Hague: Dutch Potato Office.
5. Lemaga, B., *et al.* 1994. Production constraints and some improved technologies of potato production in Ethiopia [unpublished report]. Addis Ababa, Ethiopia: Institute of Agricultural Research.
6. FAO. 1986. Farm structures in tropical climates. In *FAO/SIDA Cooperative Programme: Rural Structures in East and Southeast Africa*, ed. L. P. Bengtsson and J. H. Whitaker. FAO, Rome, Italy.
7. Scheer, A. 1996. Ventilatiesystemen voor kistenbewaring aardappelen [Ventilation systems in crate stores for potatoes]. *Landbouwmechanisatie* 47(9):16–18.
8. van der Schild, J. H. W. 1986. Aardappelbewaring: van inschuren tot afleveren [Potato storage: Loading to unloading stores]. Institute for Storage and Processing of Orable Products, Verweij Wageningen.
9. Scheer, A. 1990. Mechanische koeling van pootgoed en consumptieaardappelen [Mechanical cooling of seed and consumer potatoes]. *Landbouwmechanisatie* 41(8):7–10.
10. *Potato Storage*. 1985. Stoneleigh, UK: National Agricultural Centre.

11. Heslen, J. C. 1987. Potato storage in temperate climates. Publication no. 370; Institute for Storage and Processing of Arable Products.
12. Rastovski, A., and A. van Es. 1987. *Storage of Potatoes: Postharvest Behaviour, Store Design, Storage Practice, Handling*. Institute for Storage and Processing of Orable Products, Pudoc Wageningen. Centre for Agricultural Publishing and Documentation, Wageningen, Netherlands.
13. Irvine, D. A., D. S. Jayas, and G. Mazza. 1993. Resistance to airflow through clean and soiled potatoes. *Trans. ASAE* 36:1405–1410.
14. Scheer, A. 1991. Mechanische koeling van aardappelen (mechanical cooling of potatoes). *Landbouwmechanisatie* 42(1):64–66.
15. Van't Ooster, A. 1996. Engineering in arable farms: Potato storage. Lecture book, Agricultural Engineering, Wageningen Agricultural University.
16. Boel, R. L. A. 1991. Validatie en uitbreiding van een bestaand model voor de simulatie van het thermisch en hygrisch gedrag van een aardappelstapelings gebaseerd op het programma BFEP [Validation and development of an existing model for simulation of the thermal and hygric behavior of a potato bulk store with BFEP]. MSc-Thesis. Department of Agricultural Engineering and Physics, Wageningen Agricultural University. (not published).
17. Hendrikse, M. H. 1985. Bouwfysische aspecten van aardappelbewaarplassen [Physical aspects of potato stores]. MSc-Thesis Department Civil Engineering, TU-Delft, nr. C-042, Delft. (not published)
18. Beukema, J. J. 1980. Heat and mass transfer during cooling and storage of agricultural products as influenced by natural convection. Ph.D. diss., Wageningen Agricultural University, Pudoc Wageningen.
19. Bird, R. B., W. E. Stewart, and E. N. Lightfoot. 1960. *Transport phenomena*. New York: John Wiley and Sons.
20. Wilson J. O., L. D. Albright, J. M. Walker. 1983. Ventilation Air Distribution. Chapter in. *Ventilation of Agricultural Structures*, eds. M. A. Hellickson, J. M. Walker, J. A. Basselman. St. Joseph, MI: ASAE.
21. ASHRAE. 1989. *Handbook of Fundamentals* (SI edition). ed. R. A. Parsons Atlanta: Author.
22. Boer, L. A. 1995. Modelling van ventilatiesystemen bij de bewaring van aardappelen [Modelling of ventilation systems in stores for potatoes]. MSc-Thesis Department of Agricultural Engineering and Physics, Wageningen Agricultural University. (not published)
23. Bakker-Arkema, F. W., R. J. Patterson, and W. G. Bickert. 1969. Static pressure airflow relationship in packed beds of granular biological materials such as cherry pits. *Trans. ASAE* 12:134–136.
24. Patterson, R. J., F. W. Bakker-Arkema, and W. G. Bickert. 1971. Static pressure airflow relationships in packed beds of granular biological materials such as grain—II. *Trans. ASAE* 14:172–174.
25. Hunter, J. H. 1986. Heat of respiration and weight loss from potatoes in storage. In *Engineering for Potatoes*, ed. B. F. Cargill. St. Joseph, MI: Michigan State University & American Society of Agricultural Engineers.

26. Small, D., and D. Hodkinson. 1989. Performance of potato ventilation ducts. *Trans. ASAE* 32:1029–1037.
27. Cloud, H. A., and R. V. Morey. 1980. Distribution duct erformance for through ventilation of stored potatoes. *Trans. ASAE* 23:1213–1218.
28. Simmelink, J. G. 1996. Techniek van boxen en hallenvullers [Technical description of box and cell loaders]. *Landbouwmecanisatie* 47(8):20–21.
29. Delleman, J. 1993 Kwaliteits Controle bij aardappelontvangst [Quality guard system at delivery of a potato batch]. *Aardappelwereld*, 47 (12): 23–25.

2.3 Onion Storage

Linus U. Opara and Martin Geyer

2.3.1 Economic Importance of Onions

Edible Alliums are important vegetables worldwide. Preeminent among them in terms of volume grown and traded is the common onion grown for bulbs. In terms of global weight of vegetables produced, at nearly 28 million tons per annum, only tomatoes and cabbages exceed bulb onions in importance [1]. International trade is estimated at about 2 million tons annually, worth about US\$400 million.

Onions (*Allium cepa* L.) are highly valued worldwide for their flavor and for their nutritional value in supplying minor constituents such as minerals and trace elements (Table 2.10). The bulbs are boiled and used in soups and stews, fried, or eaten raw. They are also preserved in the form of pickles. Onion leaves, especially from the Spring onion, are also used in salads and soup.

Table 2.10. Representative values of nutrients of onion bulbs (*Allium cepa* var. *cepa*) and leaves (*Allium fistulosum*) per 100 g edible portion

Major Nutrients	Bulbs	Leaves	
Water (g)	87	90	91
Calories	48	36	30
Protein (g)	1.5	1.8	1.6
Fat (g)	Trace	0.5	0.3
Carbohydrate (g)	11	6	6
Fiber (g)	0.5	1.0	0.8
Calcium (mg)	30	40	55
Phosphorous (mg)	—	—	41
Iron (mg)	0.5	3.0	1.1
Vitamins			
β-carotene equivalent (μg)	Trace	328	630
Thiamine (mg)	0.04	0.05	0.06
Riboflavin (mg)	0.02	0.10	0.08
Niacin (mg)	0.3	0.5	0.5
Ascorbic acid (mg)	10	50	19

Sources: [2, 3].

Onions are a major crop in the tropics, which account for nearly 30% of total global production [4]. Estimated loss of total crop in these countries is high and can reach 20% to 95% [5]. Losses between wholesale and retail of over 9% have been reported for Spring onions [6]. Although some tropical countries are net importers, export potential of onions is developing in several tropical regions partly because if dried and packed properly the bulbs can be transported for considerable distances without deteriorating. Storage for several months also is possible if suitable bulb temperatures can be maintained.

Proper storage environment is critical to minimize bulb softening, shriveling, weight loss, and development of storage rots and decay. Different cultivars have variable storage life. In general, poor-keeping cultivars are less pungent [7] and have a low dry-matter content [8], a low refractive index [9, 10], and high relative rate of water loss and total water loss, especially in the period immediately following harvest. Poor-storing cultivars also are more susceptible to storage rots, sprout more readily [11], and benefit more from “curing.”

2.3.2 Physiology and Quality

The commercially grown bulb onion is a biennial crop with origin in Asia. The bulbs are naturally dormant organs adapted to maintaining the plant as viable during a period unfavorable for growth. In the native habitat of the wild ancestors of onions and garlic the bulbs may have enabled the plants to survive periods of summer drought and winter cold [1]. The onion shows a distinctly marked dormancy between the vegetative and the generative growth periods. Therefore, bulbs are natural storage organs, well adapted for long-term crop storage.

The outer dry skins are very important for maintaining the dormancy, preventing water loss, and excluding pathogens. Bulb storage rests on knowledge of the physiology plus a knowledge of the pathology of diseases of stored bulbs. Depending on variety, the dormancy and storage period ranges from a few days to several months. The storage life depends also on climatic conditions (especially temperature) during storage. The dormancy is shortened by external stimulation such as mechanical stress during harvest and handling, lighting during storage, and fluctuation of storage temperature and humidity.

During dormancy the bulb is protected by the outer scales. In this way the outer scales lose water and form dry skins while the inner scales stay fresh and firm. As dormancy declines the sprout leaves elongate and become visible. Sprout development takes energy from all scales and causes the bulbs to become soft, resulting in quality loss.

Temperature Effects

Sprouting is depressed during dormancy at lower and higher temperatures. The rate of elongation of sprouts within the bulb and the rate of leaf initiation were much faster at 15 than at 0 or 30°C. Therefore, sprout development in onion bulbs, unlike most physiological processes, does not increase in rate progressively as temperature increases. Once sprouting has occurred in rooted bulbs, sprout growth rate increases progressively with temperature [1].

Metabolic Activity

Respiration rates of produce indicate the degree of metabolic activity and provide useful insights in the design of storage systems for environmental and atmospheric control.

**Table 2.11. Respiration rates (CO₂ production) of onions
(in mg·kg⁻¹·h⁻¹)**

	0°C	4–5°C	10°C	15–16°C	20–21°C
Dry onions	3 3	3–4 5	7–8 7	10–11 7	14–198
Green onions	10–32	17–39	36–62	66–115	79–178

The rate of postharvest deterioration (spoilage) of produce generally is proportional to the rate of respiration. Bulb onions have a low respiration rate (3–4 mg CO₂·kg⁻¹·h⁻¹ at 5°C), and this increases with corresponding increases in temperature. Green onions have higher respiration rates, comparable to leafy vegetables, at the same temperature (Table 2.11). A low oxygen level in the storage chamber halves the rate of respiration [12].

In storage, as time progresses, the rate of respiration increases. If bulbs are wounded, their rate of respiration increases and reaches a maximum after about 12 hours. The higher level is measurable over the whole storage period [13, 14]. If the dry outer skins of onions are removed, the respiration rate of bulbs increases nearly two-fold and the rate of water loss also increases. Bulbs with the skin removed also sprout more rapidly than those with intact skins [1].

2.3.3 Quality Standards of Bulb Onions

Table 2.12 shows a summary of the requirements for meeting international quality standards. These standards must be interpreted for each type of produce. For onions, a comprehensive interpretation has been documented [15]. This interpretation applies to onions grown from cultivars of *Allium cepa* L. to be supplied fresh to the consumer, with the exception of onions with their leaves and stems still green (fresh onions), onions intended for planting (basic material), and onions intended for processing. Only the minimum requirements (these apply to both Class I and II quality standards) are presented here (Table 2.13). The onions have to be packed in new and clean packing material so that they are saved appropriately and not subjected to external and internal changes. The packages have to be designated concerning packer, kind and origin of product, and trading marks. For further details on the interpretation of the international standard, readers are referred to ref. [15]. It is important that both sorting and grading are supervised by well-trained personnel in order to achieve and maintain good quality standards.

2.3.4 Harvest and Postharvest Handling

Maturity

The condition of onion leaves is a good indicator of the maturity and general state of the bulb. Bulb onions that are to be stored should be allowed to mature fully before harvest, this occurs when the leaves bend just above the top of the bulb and fall over [16]. Storage losses at this maturity normally are lower than those harvested before the tops collapse [17]. Bulbs generally mature within 100 to 140 days of sowing, depending on the cultivar and the weather [18]. Spring onions are ready for harvesting 35 to 45 days after sowing. Harvesting should begin when 50% to 80% of the tops have gone over, before it is possible to see split skins exposing white flesh [19]. As a practical guide, one

Table 2.12. Example of an international OECD quality standard: Summary of the requirements

Requirements	Class I: Good Quality	Class II: Marketable Quality
Minimum requirements	Intact (flesh not exposed) Sound; produce affected by rotting or deterioration so as to make it unfit for consumption is excluded in all cases Clean; practically free from any foreign matter Sufficiently dry for the intended use (in the case of pickling onions, at least the first two dry skins and the stem should be completely dry) Free from abnormal external moisture Free from foreign smell and/or taste The stem must be twisted or clean-cut and must not be more than 4 cm long (except for twisted onions)	
Quality requirements		
Consistency	Firm and compact	Reasonably firm
Shape	Typical of the variety	Not typical of the variety
Color	Typical of the variety	Not typical of the variety
Defects allowed	Without evidence of growth Without hollow or tough stems Free from swelling caused by abnormal development Practically free from root tufts Light staining not affecting the last outer skin the protecting flesh	Early evidence of growth (not more than 10% for any given batch) Small healed cracks Traces of rubbing Slight marking caused by parasite or disease Slight bruising, healed, unlikely to impair keeping quantities Staining not affecting the last dry outer skin protecting the flesh
Sizing	Compulsory Minimum diameter: 10 mm Maximum deviation in diameter in each pack: 5 mm when graded between 10 mm and 20 mm 10 mm when graded between 15 mm and 25 mm 15 mm when graded between 20 mm and 40 mm 20 mm when graded between 40 mm and 70 mm 30 mm when graded between 70 mm and plus	
Tolerance		
Quality	10%	10%
Size	10%	10%
Packaging		
Presentation	In layers In bulk In "strings" of not less than 16 bulbs with completely dry stems	
Uniformity	Same origin, variety	
Packaging	Free from foreign bodies	

Source: [15].

**Table 2.13. Interpretation of the OECD international quality standard:
Minimum requirements for *Allium cepa* L.**

-
- a) Intact (outer skin included)
The onions must not have suffered any mutilation during growth or at any time of pulling, removal of the stem, packaging, handling, or any other operation.
When onions are stored and/or handled in a dry atmosphere, the outer dry skin may split and disappear. Thus small cracks in the outer dry skin, due to low air humidity, are allowed. As long as the flesh is not visible small cracks in the outer skin are not considered defects.
Absence of a part of the outer skin is allowed provided there are more dry skins and the flesh is not revealed.
- b) Sound
The onions must not be rotten or seriously affected by disease or parasites.
- c) Clean
The bulbs must be free from any impurity which may materially alter the appearance or quality.
- d) Free from any damage due to frost
Onions affected by frost rot rapidly after handling in a frozen condition and when the temperature rises above 0°C. Therefore they must not be allowed to travel.
The onion is regarded as frost-bitten when more than two of the outer layers of the flesh are affected and the flesh has a waxy appearance. A waxy appearance of the outer layers of the flesh can also be caused by mechanical handling. This slight defect does not affect the edibility of the onions. This waxy appearance of the outer layers disappears in a few days after ventilation
- e) Sufficiently dry for the intended use
At the beginning of the season, onions frequently are pulled before fully developed. Although they cannot be stored, they must be covered by a dry skin, which may be sufficiently dry for no moisture to be pressed out by the fingers, in order that any subsequent heating may be avoided. The onions must be pulled when ripe enough to meet current market standards, such that they remain sufficiently firm and do not become soft or spongy.
For onions pulled when fully developed, the expression “sufficiently dry” means that in wet weather the bulbs may be slightly wet in view of the hygroscopic properties of their outer skin, but the leaves near the neck must be fairly dry.
- f) Free from abnormal external moisture
At the time of shipment onions must show no signs of excessive moisture due to unnatural causes (such as prolonged exposure to rain) likely to impair their capacity for travel or keeping qualities.
The condensation observed immediately after cold storage is not regarded as “abnormal.”
- g) Free of foreign smell or taste
This refers especially to produce that has been in poorly kept or unsuitable cold storage facilities and which may have absorbed the odor given off by other produce on the premises.
- h) The stems must be twisted or clean-cut and must not be more than 4 cm long (except for stringed onions)
Onions are prepared either by hand or mechanically. Account will thus be taken of the overall appearance of the batch, and the presence of more than 20% of stems over 4 cm long in any one lot will be accepted as evidence that minimum requirements have not been met.
-

Source: [15].

should conduct sample counts on the number of bulbs that have fallen over in a field. When the percentage of bulbs that have fallen over reaches about 70% to 80% of total, then one should harvest the entire crop. Bulb yields up to 5 ton·ha⁻¹ have been reported [20]. Harvested crop should be allowed to dry or cure and ripen in the sun for several days after lifting.

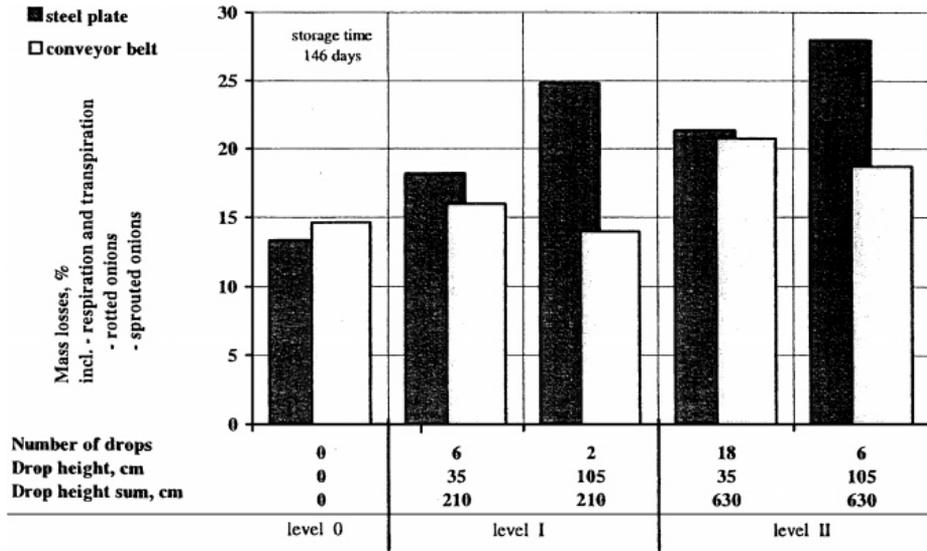


Figure 2.28. Onion storage losses as affected by number of drops, drop height, and type of impact surface.

Mechanical Damage

Onions are susceptible to physical damage during harvesting and postharvest handling. Onions often are classified as firm or hard long-day (e.g., Yellow Globe Danvers) or soft short-day (e.g., Grano/Granex types). Susceptibility to damage varies among cultivars, but soft short-day cultivars are more susceptible to damage and therefore require greater care during harvesting and handling than the hard long-day cultivars. Bulb damage results from impact and crushing on hard surfaces and bulb-to-bulb impact. Impact damage manifests as bruising or splitting of bulb tissue.

Impact tests (falls onto a concrete floor or onto other onions) using a hard-onion cultivar (e.g., Yellow Globe Danvers) have shown that the severity of damage was related to the drop height and to the size of the bulbs [21]. A drop height of 1.8 m onto a concrete surface produced an average of 50% visibly damaged onions after 120 days in cold storage. It was concluded that under similar conditions, onions should not be dropped more than 1.2 m onto a nonresilient surface. Damage from bulb-to-bulb impact was less severe, and the first onions dropped into crates often showed the most damage. Drop tests using the hard-onion cultivar *Rheinsburger balstora* showed that drop heights of 35 cm on steel plate or concrete increased respiration rate as well as mass loss after 146 days in store [13, 14]. The losses put together resulted in increasing respiration and transpiration, sprouting and decay of the bulbs. The drop height, the amount of drops and the kind of surface are responsible for increasing respiration rate and storage losses (Figs. 2.27 and 2.28). Drops higher than 50 cm on a conveyor belt and 20 cm on a hard surface should be minimized during postharvest handling operations. Hard surfaces should be adequately cushioned.

During the handling of soft onion cultivars in particular, drops greater than a few centimeters should be avoided, and machinery such as grading equipment should be padded, especially on projecting corners. Some soft cultivars (e.g., Texas Early Grano) also are susceptible to crushing if stacked in sacks. For such cultivars, packaging of bulbs in cartons is recommended for transportation and marketing. To minimize bulb damage during harvesting, the soft or short-day cultivars usually are pulled and bagged by hand in the United States, and large-scale mechanized onion-harvesting machinery is suitable only for hard onion cultivars.

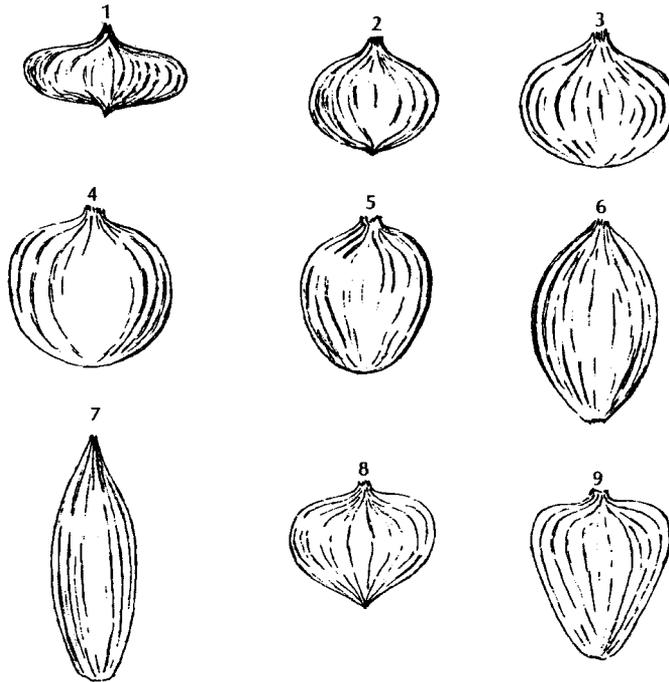
As bulbs are susceptible to physical injury such as bruising due to compression damage, bulk storage heights should not exceed 3.5 to 4 cm [1, 22]. Bulb damage by bruising and shattering can be reduced by packaging in boxes, but this may require substantial investment. In addition to the lowering of appearance quality, bruising and splitting resulting from mechanical damage also affect bulb internal-quality attributes. Experimental studies showed that bruising changed the scale texture and made the outer fleshy scale soft, flattened, and pithy in appearance when cut through [21]. Wounding also resulted in sprouting and decay on the wounded areas, and damage of freshly harvested bulbs caused the exudation of sap from the basal stem plate, resulting in microbial infection of the affected areas. The physiological effects of wounding on onion bulb are well documented [23].

Harvesting

Hand harvesting usually is carried out by levering the bulbs with a fork to loosen them and pulling the tops by hand. This is the common practice in many developing countries in which farming is manual labor-intensive. In developed countries, especially on large-scale farms, mechanical harvesting commonly is used. The harvesting techniques depend upon the weather at harvest time. In areas where warm, dry weather occurs reliably, the curing and bagging of the crop can be done in the field (two-phase harvesting). In wetter, temperate regions, mechanical harvesting and artificial heating and ventilation for drying are essential to produce reliably high-quality bulbs on a large scale.

Two-phase harvesting usually has the following steps: mowing the leaves (not cogent); stubbing, undercutting, and sieving the onions to remove stones and clods; rolling the soil in the row to get a plane surface; drying the bulbs (windrowing) 8 to 10 days in the field; turning the bulbs one to two times; harvesting, sieving, and hand grading, overloading into a trailer or in crates; and transporting. For one-phase harvesting, usually commercial potato harvesters have been adapted. After mowing the leaves the crop is harvested immediately, sieved, hand graded, and loaded onto the trailer.

Labor costs for two-phase harvesting are about 30% to 100% higher than for one-phase harvesting. The disadvantage of one-phase harvesting is the energy consumption for the drying process. Using combine harvesting [24], the standardized working hours have been calculated to be 2.7 to 2.9 h·ha⁻¹ for stubbing, 2.4 to 2.6 h·ha⁻¹ for turning and 8.9 to 11 h·ha⁻¹. The highest mechanical impacts on the bulbs occurred during loading, when the onions dropped on the uncushioned bottom of the empty trailer [14]. Reducing drop height, cushioning the bottom of the trailer, or using drop sails can reduce the incidence of bulb damage.



- | | |
|-------------------|--------------|
| 1 Flat | 5 High globe |
| 2 Thick flat | 6 Spindle |
| 3 Flattened globe | 7 Cylinder |
| 4 Globe | 8 Flat top |
| | 9 High top |

Figure 2.29. Onion shapes.

Bulb Size and Shape

Bulb size and shape are important attributes both for marketing and retention of postharvest quality. Onion-bulb shapes can be described by various standard geometries (Fig. 2.29). Bulb size affects both sprouting and water loss during storage. Studies have shown that during storage at 11°C large bulbs sprouted at a faster rate than small ones, but small onions lost weight more rapidly [25, 26].

Drying and Curing

This is the process of dehydrating the outer layers of bulb crops such as onions and garlic before storage to provide a surface barrier against water loss and microbial infection, thereby preserving the main edible tissue in a fresh state. The drying process also minimizes shrinkage by removing moisture from the interior of the bulb, reduces the occurrence of sprouting, and allows the crop to ripen before fresh consumption or long-term storage. This process is sometimes called “curing,” but the use of the word curing for onion drying is rather inaccurate, because no cell regeneration or wound healing occurs as in other root crops such as yam and cassava. Onion drying

normally is achieved with weight losses of 3% to 5% [2, 22] and up to 10% with artificial drying [27].

Traditionally, drying of onions has been carried out in the field and called *windrowing*. Windrowing involves harvesting the mature bulbs and laying them on their sides (in windrows) on the surface of the soil to dry for 1 or 2 weeks. In hot tropical climates, the bulbs should be windrowed in such a way as to reduce the exposed surface, to minimize damage due to direct exposure to the sun. In wet weather, the bulbs can take a longer time to dry and may develop higher levels of rots during storage. The side of the bulb in contact with wet soil or moisture also may develop brown strains or pixels that reduce the appearance quality and value [16]. Clearly, successful windrowing is weather-dependent and therefore not used extensively in many large-scale commercial enterprises. Bulbs harvested for storage require in total 14 to 20 days of ripening or drying before being stored. Onions also may be harvested in trays that are then stacked at the side of the field to dry. In some tropical regions, the bulbs are tied together in groups by plaiting the tops, which are then hung over poles in sheds to dry naturally.

Alternatively, harvested bulbs are taken straight from the field and artificially dried in either a store, a shed, barns, or a special drier. This method is commonly used if crops are stored in bulk, but it also can be applied to bags, boxed, or bins [28]. Bulbs are laid on racks and air is rapidly passed across the surface of the bulbs night and day [19, 27]. Drying may take 7 to 10 days and is considered complete when the necks of the bulbs have dried out and are tight and the skins shrivel when held in the hand. The control of humidity level in the store is critical. If humidity is too high, drying is delayed and fungal infection can increase. On the other hand, if relative humidity is too low (below 60%), excessive water loss and splitting of the bulb's outer skins can occur [29], and this increases storage losses and reduces bulb value. The use in well-ventilated conditions of wire mesh and air at about 30°C, 60% to 75% relative humidity, and 150 m³·h⁻¹·m⁻³ is recommended.

Sorting and Grading Before Storage

Sorting of bulbs is important before storage to ensure that only good-quality bulbs are placed in store. Any damaged, diseased, or rotten bulbs must be removed. The presence of these defects reduces storage life of affected bulbs and leads to the infection of otherwise sound produce within the store.

In developed countries separation and sorting before storage takes place during harvesting with the combine. After mechanical separation of small onions, earth, stones, and clods, up to four graders manually select damaged and rotted onions. Onions that are stored in loose bulk are separated from dirt and leaves again on their way to the shed using special facilities. It should be taken into consideration that every handling process induces mechanical load on the bulbs. In developing countries bulbs often are sorted before and after drying if they are dried in a separate structure to the store.

Grading After Storage

Grading enables the handler to package the bulbs according to quality standards and market requirements. A usual process line follows certain steps (Fig. 2.30). The steps are mostly mechanized. Transports in crates is done using fork-lifts using open transport with

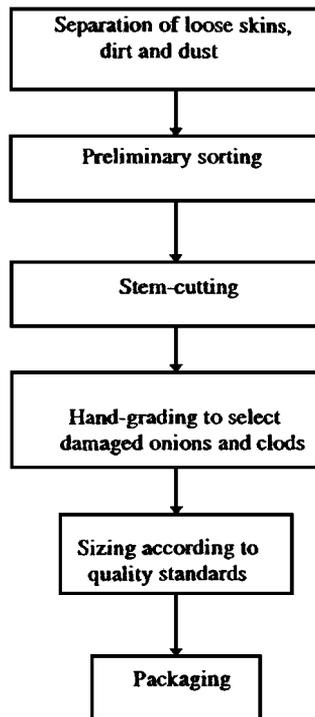


Figure 2.30. Flowchart for grading onions after storage.

conveyor belts. It must be taken into consideration that all processes induce mechanical load on bulbs.

2.3.5 Packaging

Purpose

Packaging basically facilitates handling by enabling a quantity of commodity to be treated as one unit. For onions, a package must meet the following criteria [15]: It must be strong enough to retain the required weight of onions under the conditions of transport and storage, allow sufficient ventilation for the air around the bulbs to maintain relative humidity in the required range, and in many circumstances provide a means of displaying legally required and commercially necessary information.

Types of Packaging

Different types of packaging represent different physical methods by which the onions are held. Onions can be packaged and stored in a variety of containers such as boxes, cartons, bags, bulk bins, prepacks, plastic film bags, and stretch-wrapped trays. Packages typically contain 25 kg or upwards, especially for transporting crop from field to store or during storage. The same 25-kg bags or smaller bags may be used from store to marketplace. There is limited use of small prepacks for retail sale. The choice of type

of packaging depends on size of crop, length of storage, and marketing requirements. A problem with packaging onions in boxes, net bags, and bulk bins is that if the packages are too large, airflow pattern tends to be around rather than through them. Under this condition, the respiration heat of the bulbs results in a warm, humid environment in the center of the package, giving rise to decay or sprouting. In large stores, the capital investment in packaging may be quite substantial.

Bags

Bags (sacks and nets) used for onion packaging fall into three groups: general-purpose jute sacks, as used for many agricultural commodities; open-weave sacks of sisal-like fiber; open-mesh nets, normally of plastic materials; and big bags, used alternatively to crates, containing up to 1000 kg.

Jute sacks are readily available in most developing countries, but their disadvantages [15] include that they generally are too large, possibly containing 100 kg of onions, and hence difficult to handle and increasing risk of mechanical damage; bulbs are not visible through the fabric, making it more difficult to monitor condition during storage; there is some resistance to airflow if they are used in an aerated store; they are difficult to label effectively; and recycled sacks may encourage spread of postharvest diseases.

Sisal sacks are made from sisal-like hard fibers and have an open weave, with thick threads spaced between about 10 and 15 cm apart. The rough nature of the fiber provides a sufficiently stable weave. These sacks are similar to jute sacks, but allow limited visibility of the onions and create less impedance to airflow.

Open-mesh nets are the most widely used package for onions, and they are normally red or orange in color. The slippery nature of plastics can result in the movement of the threads, allowing large holes to open up. To overcome this problem, alternative nets are produced industrially to give fully stable mesh and a stronger bag. The principal techniques include using extruded net from high-density polyvinyl chloride (PVC), knitted (warp-knitted) and asymmetric construction, and special weave in which weft threads are doubled, and twisted.

These nets also are slowly degraded by sunlight, and should not be left outdoors for long periods before use. In comparison with the other types of bags, they offer several advantages, including light weight, small bulk when empty, general availability in 12.5- and 25-kg sizes, fairly good visibility of bulbs, excellent ventilation, good hygiene, easy closing (draw-string types only), and the fact that crop brand and marketing information may be printed around the middle of the bag for easy identification.

Trays, Boxes/Cartons, and Bins

A range of rigid containers are used to package onions for transportation, marketing, and storage. The principal rigid containers are trays (containing 10–15 kg of onions each), boxes (containing up to 25 kg), and bulk bins (containing up to 1000 kg). These types of packaging enable segregation of onions into different cultivars or sources. Choice of packaging material is important, as wooden bins, for example, are liable to termite attack and weathering during off-season. Rigid containers also are expensive, need regular maintenance, and require a forklift for handling larger containers. Where rigid containers are used for onion storage, building design is simpler than that for large-scale loose bulk

storage, as reinforcement of retaining walls is not required to support the bulbs. Handling damage of bulbs during filling and emptying can be frequent, but damage is reduced during store loading and unloading operations in comparison with loose bulk handling and storage.

Special attention is required during stacking of containers to ensure that the ventilation air is forced through the containers of bulbs and not around them. However, rigid containers facilitate regular inspection of produce, and if problems occur with the stack, the area affected often is limited to a few trays, boxes, or bins that may be more easily isolated and removed than in a loose bulk handling system.

Prepacks

The weight of retail prepacks for onions typically is in the range of 0.5 to 1.5 kg, and prepacks are associated with self-service retailing. Prepacking of onions sold in a supermarket allows price to be attached to produce; collates a number of pieces into one unit of sale and may promote sale of a larger quantity than would be purchased otherwise; provides a clean odorless unit for the customer to handle; and reduces time spent at the check-out [15]. The use of weight/price-labeling machines and bar coding has reduced the need to pack to fixed nominal weights. During preparation for retail, the quantity of produce is measured by hand or machine and filled into the pack. Then the actual weight and price or bar code are calculated automatically and printed on a label that is attached to the package. This mechanized weighing and labeling system assists the packer in accurate record keeping and avoids losses due to inaccurate pack weights. The three main types of onion prepacks are nets, plastic film bags, and stretch-wrapped trays:

Nets are in essence smaller versions of the nets used for bulk handling. Net prepacks are preferable to the other types of onion prepacks because they do not promote an increase in relative humidity inside the package. Netting is available as a tube, which is then loaded onto a metal tube on the packing machine. The prepack can be closed in two alternative ways: The two ends can be closed using a metal clip, and a card label can be attached simultaneously; or one end can be clipped and the other closed by stitching, through a card label.

Plastic film bags are cheaper than nets if made from low-density polyethylene or polypropylene films, but the shelf life of onions is likely less than in a net. The bags must be perforated to assist air and gas exchange to counteract the increase in humidity inside the bag as the onions respire. The recommended size of holes is 6 mm in diameter, and the number of holes should not be less than eight in a 1-kg pack [15]. Methods for filling the film bags range from manual to full automation, and a bunched closure using adhesive tape is considered most appropriate.

Stretch-wrapped trays are used for prepacking a small number of pieces, usually four to six. Depending on availability and price, the tray is available in a range of materials such as clear plastic, expanded plastic, or molded pulp. The film is made from a special formulation of PVC or polyethylene and is usually very thin (12–15 μm) with a very high vapor-transmission rate. The relative humidity inside the pack tends to rise, and packed onions must be inspected regularly for onset of deterioration. The plastic film must be heat-sealed and a range of equipment is available from manual to full automation. The

packing requires electricity, and this limits the use of stretch wrapping in rural tropical areas.

Other Systems

Many other methods of holding onions for transportation or storage are practiced that cannot readily be classified under any of the previously discussed types of packaging.

Tying the bulbs together by means of their tops to produce a bunch of bulbs is also a form of packaging. It is suitable for transporting small quantities of crop, and during storage the bunches are hung from the roof or from special racks. This is particularly suitable for rural small-crop handling and marketing but is not compatible with large-scale operations due to the high labor intensity and the need to hang the strings in storage.

Shelves can be made from either wooden slats or metal mesh on a wooden or metal frame and usually are fixed in position with the bulbs loaded and unloaded in the store. Ventilation (natural or forced) usually is achieved by passing air over the shelves. To achieve adequate aeration of the bulbs, the depth of bulbs on the shelves should be limited to 10 cm.

Rather than in any container onions also are stored in loose bulk, with the bulbs heaped directly on the floor or elevated platform. Because they are not restrained, the bulbs roll during store loading to completely fill the storage space. Bulk storage permits maximum utilization of store space, and uniform aeration is easier to achieve than in stacks of bags or other rigid packaging. However, where bulk storage is to be implemented the retaining walls must be strengthened when storing larger quantities of bulbs, and arrangements need to be made for rebagging before subsequent marketing. It also is difficult to inspect bulbs regularly under these storage conditions. Loose bulk is most suitable for large-scale operations in which forced ventilation is provided during long-term storage; however, because of their softness, the sweet cultivars such as *Vidalia* Sweets should not be stored in loose bulk.

2.3.6 Bulb-Storage Requirements

Preparation for Storage

The aim of storage is to extend the period of availability of crop, maintain optimum bulb quality and, minimize losses from physical, physiological, and pathological agents. During preparation for marketing and storage, selected bulbs should be firm and the neck dry and thin; thick-necked bulbs should be discarded [18, 19]. Skin color should be typical of the cultivar. Microbial infections such as *Aspergillus niger* occur during production of onions, but these only develop on the bulbs during storage if the storage environment is conducive for their growth. Prior to storage, the crop must be cleaned and graded, and all damaged or diseased bulbs removed. Careful harvest and prestorage treatments with minimal mechanical loads are important to achieve a long storage period. Storeroom temperature, relative humidity, and atmospheric composition influence the length of storage that can be achieved without significant storage losses and reduction of bulb quality.

Table 2.14. Recommended refrigerated storage conditions for onion bulbs

Temperature (°C)	Relative Humidity (%)	Length of Storage
-3-0	70-75	6 mo
-3	85-90	5-7 mo
-2	75-85	300 d
-2-(-0.6)	75-80	6 mo
-1-0	70-80	6-8 mo
-0.6	78-81	6-7 mo
0	75-85	6 mo
0	65-75	—
0	70-75	20-24 wk ^a
0	70-75	—
0	65-70	1-2 mo ^b
0	65-70	6-8 mo ^c
0	—	230 d
0	70-75 or 90-95	Up to 120 d
0	80-85	30-35 wk ^d
1-2	80-85	30-35 wk ^e
1	87	—
1.1	70-75	16-20 wk ^f
4	—	170 d
8	—	120 d
12	—	About 90 d
20	—	25 d

Sources: [12, 18, 28].

^a With 16.3% loss (red onion).

^b Bermuda cultivar.

^c Globe cultivar.

^d With 14.2% loss (red onion).

^e Superba cultivar.

^f Optimum storage conditions, 7% maximum water loss before becoming unsaleable.

Low-temperature Storage

Ranges of temperatures and relative humidities have been recommended for storage of onions (Table 2.14). For successful low-temperature storage, good ventilation and a low humidity level in the range of 70% to 75% is essential. For good-quality crop, the period of storage varies but may be up to 200 days [18]. For maximum storage period and minimum losses bulbs should be fully mature at harvest and dried until the “neck” of the bulb is tight. For large-scale commercial storage, onions usually are stored under refrigeration, and the most commonly recommended conditions are 0°C with 70% to 75% relative humidity. Regular ventilation and monitoring of both temperature and relative humidity in the store are necessary to avoid significant fluctuations in environmental conditions.

During the first few days of bulb storage the fans should provide an adequate airflow to remove water in the outer skins and to dry bruises. High airspeed is needed for a

Table 2.15. Recommended refrigerated storage conditions for Spring (green) onion

Temperature (°C)	Relative Humidity (%)	Length of Storage
0	95–98	—
0	90–95	A few days
0	90–95	2 wk
0	95–100	—
0–1	95–100	1–3 wk

Adapted from [16].

period of up to 1 week, until the skin of the upper onion layers in the bulk rustles. High humidities will cause development of roots and promote rotting; higher temperatures will result in sprouting and promote development of pathological disorders such as *Botrytis* rots [28].

Bulbs freeze below -3°C . Spring (green) onions store best at about 0°C and very high humidity ($>95\%$) (Table 2.15). Maximum length of storage at these conditions varies from just a few days to about 3 weeks. Low-temperature storage of onions can be achieved under both ambient and refrigerated storage conditions; however, ventilation must be applied carefully inside the store to achieve the required temperature and humidity levels without inducing condensation of water on the surface.

High-temperature Storage

Onions also may be stored at high temperatures of over 25°C at a range of relative humidities (75% to 85%) that are sufficient to minimize water loss. Storage at temperatures of 25 to 30°C has been shown to reduce sprouting and root growth compared to cold storage at 10 to 20°C ; however, weight loss, desiccation of bulbs, and rots occurred at high levels, making the system uneconomic for long periods [4, 17]. High-temperature storage of onions can be achieved under both ambient and heated storage conditions; however, ventilation must be applied carefully inside the store to achieve the required temperature and humidity levels.

Direct Harvest Storage System

Both low-temperature and high-temperature storage require that the outside layers of the bulb be dried and the outer skin cured prior to onion storage. These can pose problems in situations in which the climatic condition is unpredictable during the harvest period, which can result in inadequate drying and conditioning of bulbs. To overcome these problems, the direct harvest system has been developed and used extensively by growers in the United Kingdom since the early 1980s. The bulbs are harvested while green, topped, loaded into store, dried, and cured using a well-controlled ventilation system, and thereafter they are held in long-term low-temperature storage as required (Table 2.16). During stage I, removal of excessive surface moisture is achieved at high airflow rates, ignoring the rh of the air. Stage II is completed when the skins have been cured on the bulb. Adequate control of the storage condition at the various stages is critical to the success of this storage system in maintaining required bulb quality.

Table 2.16. Environmental regimens used direct harvest storage system

Stage	Duration	Temperature	Humidity (%)	Airflow Rate (m ³ s ⁻¹ ton ⁻¹)	Comments
I	3–5 d	30–32°C	—	0.12	Removal of surface water
II	20 d (approximate)	26°C initially, slowly reduced to 15°C	65–75	0.048	Removal of surface moisture, drying and curing of the skins, and sealing; completion indicated by rustling of skins when handled
III	As required	0–5°C	65–75	—	Minimize respiration, extended dormancy; up to 10 mo storage possible
IV	7 d (approximate)	Above dew point of air in grading shed	65–75	—	Bulb warming to avoid condensation of moisture during grading and reduce susceptibility to bruising; condensation on bulb also reduces appearance quality if dust and dirt stick on bulb

Source: [15].

Table 2.17. Recommended controlled-atmosphere composition for storage of onion bulbs

Carbon Dioxide (%)	Oxygen (%)	Temperature (°C)
0–5	1–2	0–5
0–5	0–1	0–5
5	3	1
5	5	4–5
10	3	4–5

Adapted from [16].

Controlled-Atmosphere (CA) Storage

A range of CA compositions in combination with cold-storage temperatures have been reported for storage of onions bulbs (Table 2.17). Spring onions generally tolerate higher CO₂ and O₂ levels than bulb onions. The levels of CO₂ and O₂ required also vary depending on the storage temperature (Table 2.18).

Commercial CA storage of onion bulbs generally is limited partly because of variable success and inconsistent results with bulb quality. However, high carbon-dioxide (0%–5%) and low oxygen (1%–3%) levels in combination with low-temperature storage have been shown to reduce sprouting and root growth [30, 31]. The combination of CA storage (5% CO₂, 3% O₂) and refrigerated storage (1°C) also resulted in 99% of the

Table 2.18. Recommended controlled-atmosphere composition for storage of Spring (green) onions

Carbon Dioxide (%)	Oxygen (%)	Temperature (°C)	Comments
5	1	0	Stored for 6–8 wk
0–5	2–3	0–5	Had only a slight effect
10–20	2–4	—	—
10–20	1–2	0–5	Had only a fair effect but was of limited commercial use

Adapted from [16].

onion bulbs being considered marketable after 7 months storage; however, 9% weight loss occurred [32].

Response of onions to CA storage is cultivar-dependent, and it is recommended that trials be conducted under local conditions to determine the appropriate level of gas composition for storing local cultivars. In general, the pungency of pungent onions increases after CA storage. For the Vidalia Sweets, which are known for their sweetness and low pungency, the recommended storage conditions [33] are 1°C, 70% to 80% relative humidity, 3% O₂, 5% CO₂, 92% N₂, and a ventilation rate of 5 m³·h⁻¹·m⁻³.

Currently, the application of CA technology for onion storage is limited almost entirely to the temperate climates in the developed countries. However, it has considerable potential to reduce weight loss and extend storage life in tropical countries if technically appropriate and economically feasible options can be implemented. Bulb weight loss under CA conditions is about 1.5% per month compared with ambient storage losses (excluding rots and sprouting) of 2% to 3% in a tropical condition. Similarly, onion weight loss was limited to 15% over 7 months of cool CA storage, compared with the 40% typical of onions held under heated forced-air ventilated storage in a tropical environment [15].

Generalized Effects of Storage Regimes

The purpose of onion storage is to extend bulb storage life and minimize the loss of quality. It is therefore important that both temperature and relative humidity (Fig. 2.31) in the store are maintained at levels that inhibit sprouting and development of storage pathogens as well as control excessive water loss from the bulbs, which results in shrivel and weight loss.

2.3.7 Control of Storage Disorders and Diseases

During postharvest handling and storage, bulbs are susceptible to sprouting and a range of diseases due to infection by microorganisms. If these are not adequately controlled, considerable storage losses and reduction of quality attributes can occur. Bulbs may sprout and also develop rots at higher storage temperatures or when they are removed from store for marketing.

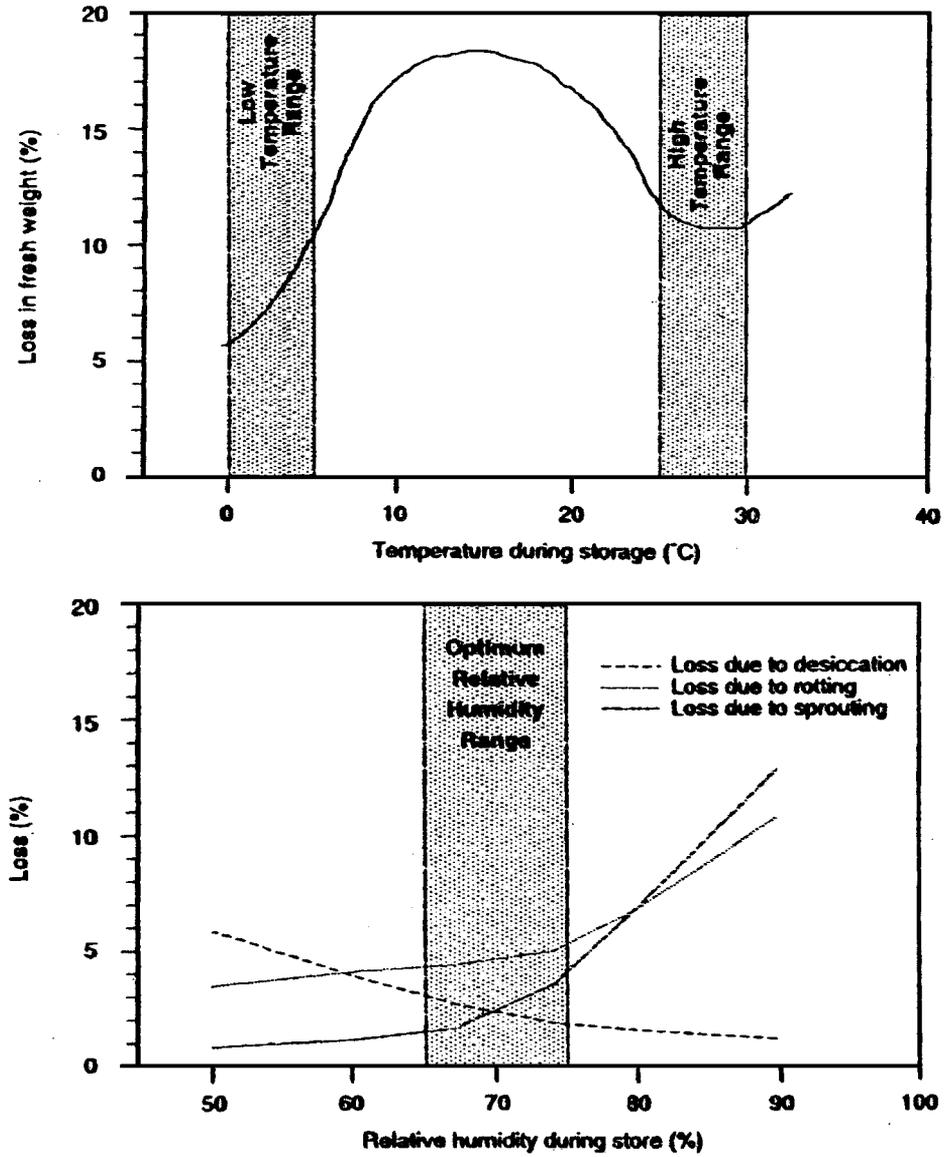


Figure 2.31. Generalized effects of temperature and relative humidity on onion quality during storage. (Source: [15])

Control of Sprouting

Various chemicals and gamma irradiation have been shown to prevent sprouting of onions during storage [4]. Application of doses of 20 to 30 Gy irradiation as soon as possible after harvest prevents sprouting. The effectiveness is highly reduced if irradiation is delayed [34]. A chemical sprout-suppressant called maleic hydrazide (MH) is the most commonly used. Application of MH at 2500 parts per million on the growing crop a few weeks before harvest prevents sprouting during storage of onions [4, 18] and thus extends their length of storage. It is important to apply the chemical treatment during the period of crop growth so that the chemical can be translocated to the apex of the growing point towards the center of the bulb. Foliar application rates of 8.5 L·ha⁻¹ at 10% fallow [19] and 5.4 L of 36% active ingredient preparation in about 600 L of water per hectare when 30% to 50% of the tops have fallen over have been recommended [28].

Spray timing is critical but not less than 10 days before harvesting. Also, MH should not be applied to very immature bulbs, because too much is absorbed into the growing point, which then dies; this often is followed by a brown bacterial rot. Bulbs also remain very soft. In any local situation, consult the manufacturer's recommendation to determine the appropriate time and application rate. It is important to note that the use of many agrochemicals including MH is governed by legislation in several countries, and this legislation must be consulted before chemical usage.

Control of Postharvest Diseases

The most important postharvest diseases of onions are neck rot or grey mold (*Botrytis allii* Munn), basal bulb rot (*Fusarium oxysporum* Schlecht ex Fr), and black mould (*Aspergillus niger* Van Tiegh). Neck rot is a storage disease and is widespread where onions are grown. It may develop at any point of the bulb, but it is most common on the damaged neck tissues. Affected areas develop a brown soft rot followed by a dense cover of grey–green powdery spores. Infection is seed-borne, and it has been suggested that there is no bulb-to-bulb transmission during storage [35]. Control of the disease has been accomplished by dusting seeds with benomyl at a rate of 1 g active material per kilogram of seed before planting.

Basal bulb rot is a soil-borne disease that can affect onions at any stage of development and causes death of seedlings, especially in warm climates. If the roots and basal plate of the growing bulbs get infected at a late stage of development, external symptoms may not appear until storage at ambient temperatures, during which affected bulbs quickly develop a semiwatery rot and eventually become desiccated empty shells. The fungus is thought to survive from season to season in the field on weed hosts. The development of the disease in storage can be inhibited by holding the bulbs under refrigeration at 0 to 1°C, and experimental trials have shown that dipping the seeds in suspension of benomyl (1000 ppm) for 15 minutes gives some degree of control.

During storage, black mold is characterized by the appearance of black powdery spore masses on the outer scales of the bulbs, especially along the vascular strands of veins. The effect is not generally devastating, although localized spots can be severe. In general, white onions are less susceptible than colored varieties, and the disease is controlled during cold storage at 0 to 1°C [28].

2.3.8 Types of Storage Structures

Traditional Simple Shelters

Several simple onion-storage structures have been developed and modified over the years such as mud, dung, and straw cottages commonly found in tropical developing countries. The principal function of these simple shelters is to protect harvested crop from the elements. These structures have a slatted wooden stage inside on which the bulbs are piled up to about 1 m deep, and ventilation is achieved by the natural prevailing wind passing through the structure. Square straw cottages are built on upright poles driven into the ground. Nails are then driven into the poles, and bunches of onions, plaited together by their tops, are suspended from these nails.

Windbreaks also provide a traditional method of storing onions in both developing and developed countries, and up to 6 months of storage have been claimed by some farmers [16]. They are made in the field from a wooden base that allows a space below the onion stack and about 30 cm from the ground. Two parallel rows of stakes about 1 m apart are driven into the ground around the wooden base, and wire mesh is stretched between the stakes and across the two ends of the windbreak. The stakes should be slightly sloping outwards and about 2 m high. Onions are then placed within the cage, topped with 15 to 20 cm of loose straw, and covered with polyethylene sheets (about 500-gauge), which are tied down and weighted with bricks. To maximize ventilation and drying of bulbs, windbreaks should be built with the longest axis at right angles to the prevailing wind.

In addition to existing traditional stores such as those built from straw (Fig. 2.32) a variety of improved small-scale ambient structures for onion storage have been developed in many tropical countries (Figs. 2.33–2.35).



Figure 2.32. Onion store built from straw. (Source: [28])

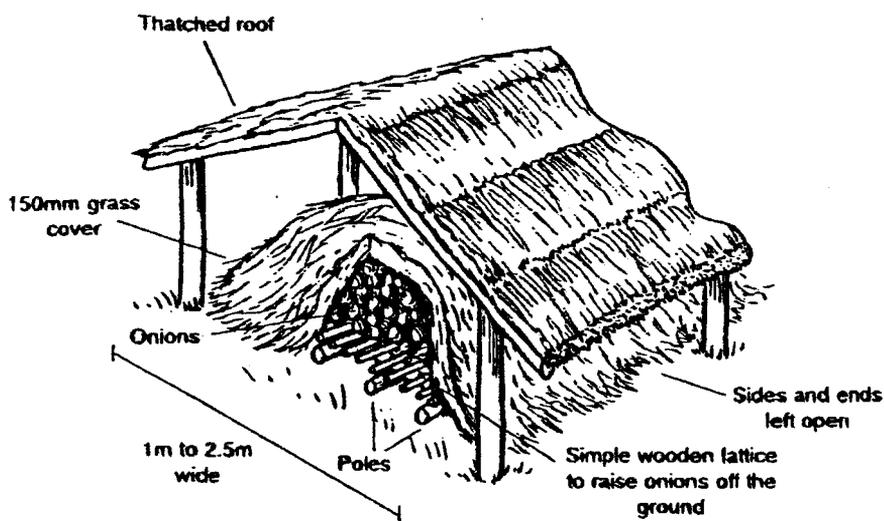


Figure 2.33. Covered clamp raised from the ground. (Source: [36])

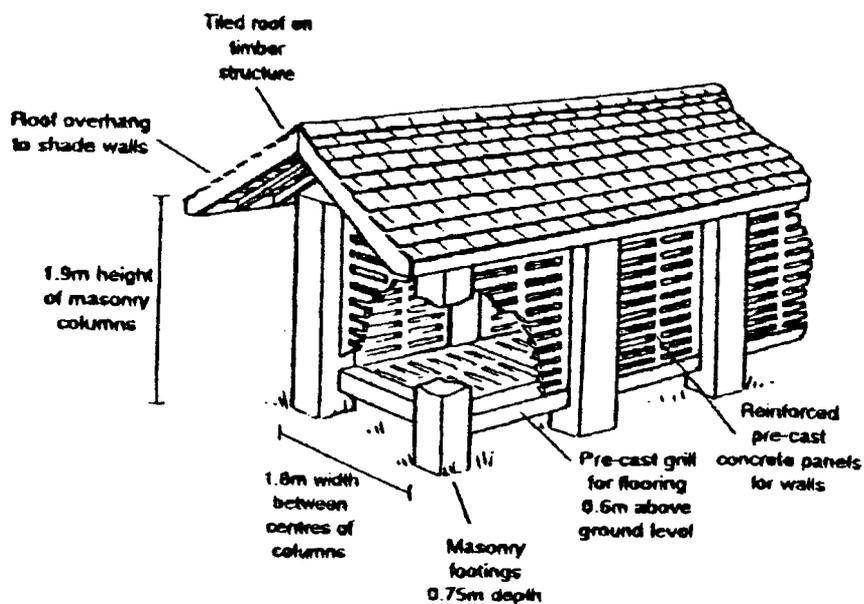


Figure 2.34. Improved design chawl for onion storage. (Source: [15])

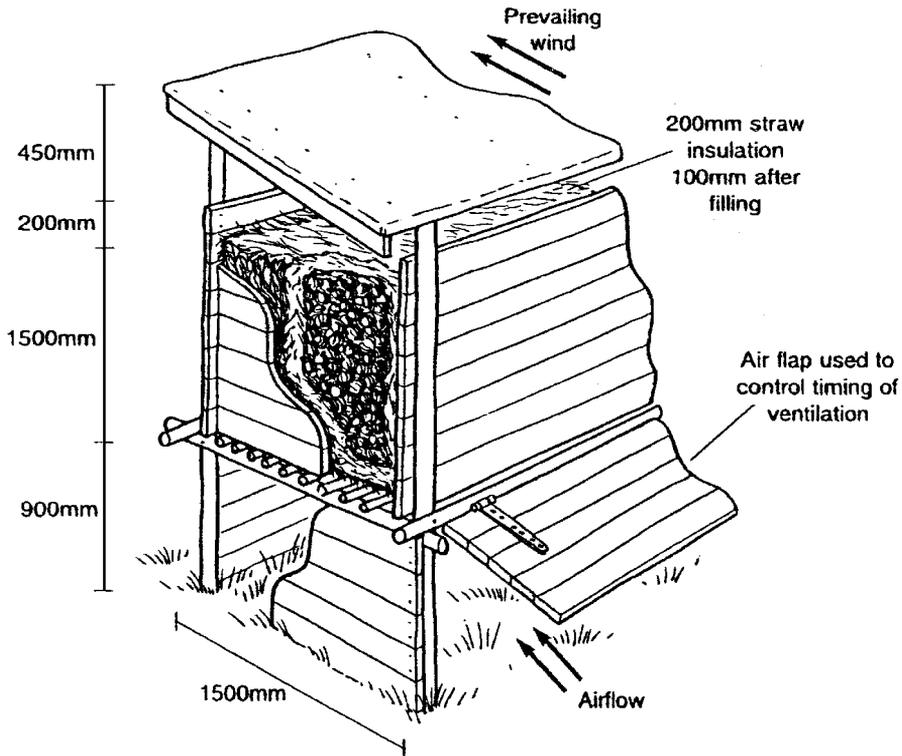


Figure 2.35. Improved naturally ventilated onion store. (Source: [36])

Ventilated Stores

Forced-ventilated Stores

Forced-ventilated stores use heated air for the drying and storage of onions. Heated air from a fan-burner is channeled to the onion bin or storage chamber, which may be constructed of metal weld-mesh (Figs. 2.36–2.38). In these stores, uniform air distribution is achieved by an arrangement of plenum chambers and laterals.

Night-ventilated Stores

These stores use the variation between night and day temperature to keep stores cool, especially in hot tropical climates. The following features are important in the design of a night-ventilated store [16]: It should be well insulated and the crop placed inside; a differential thermostat should be installed to constantly compare the outside air temperature with the inside store temperature; and a fan should be installed into the store that is switched on when the outside temperature is lower than the temperature within the store and switched off at night when the temperatures have equalized. Performance evaluation of a night-ventilated onion store (Fig. 2.39) based on the above principles

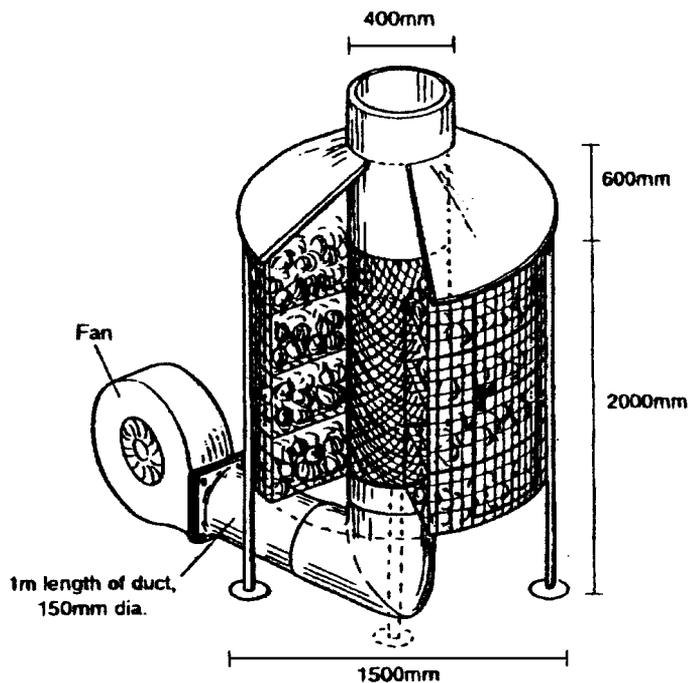


Figure 2.36. Forced-ventilated onion store. (Source: [37])

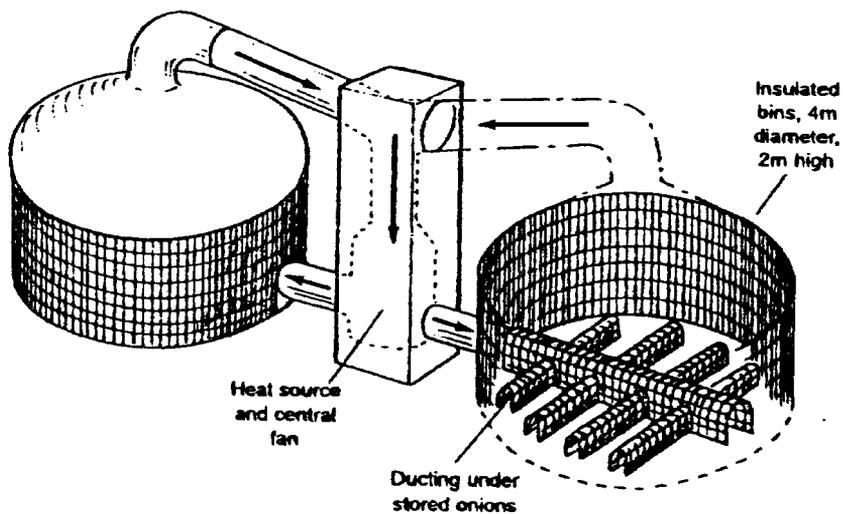


Figure 2.37. Low-cost, weld-mesh onion store. (Source: [38])

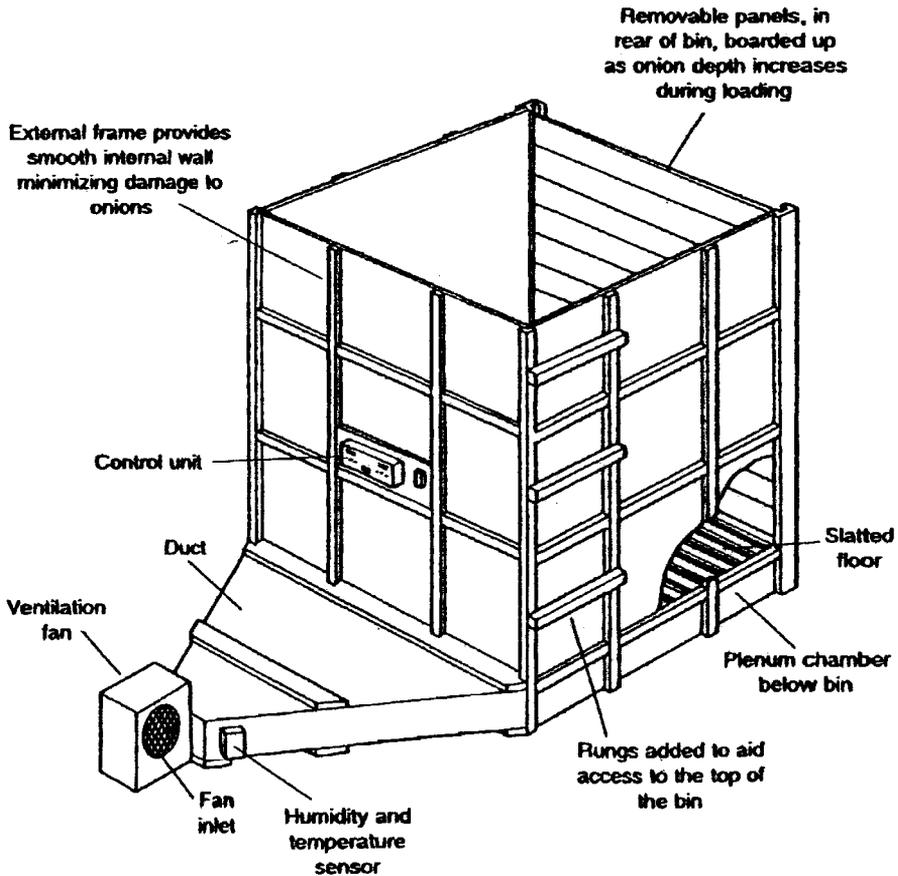


Figure 2.38. Natural Resources Institute–designed onion storage bin. (Source: [15])

showed that onions could be maintained at an even temperature very close to the minimum night temperature. Although total storage losses were high, they were lower than those obtained using a traditional method of storage (Table 2.19).

Air-conditioned Stores

Onion-storage structures in this category can vary from well-insulated buildings with heaters to prevent freezing to cold-storage rooms that provide constant airflow temperatures, and to complete CA stores. In major producing regions in the developed countries, a considerable quantity of onions are held in cold-storage warehouses located in the large terminal markets. Refrigeration technology is used to keep these warehouses at about 0°C throughout the storage period, and the onions are moved out gradually into the marketing channels [4].

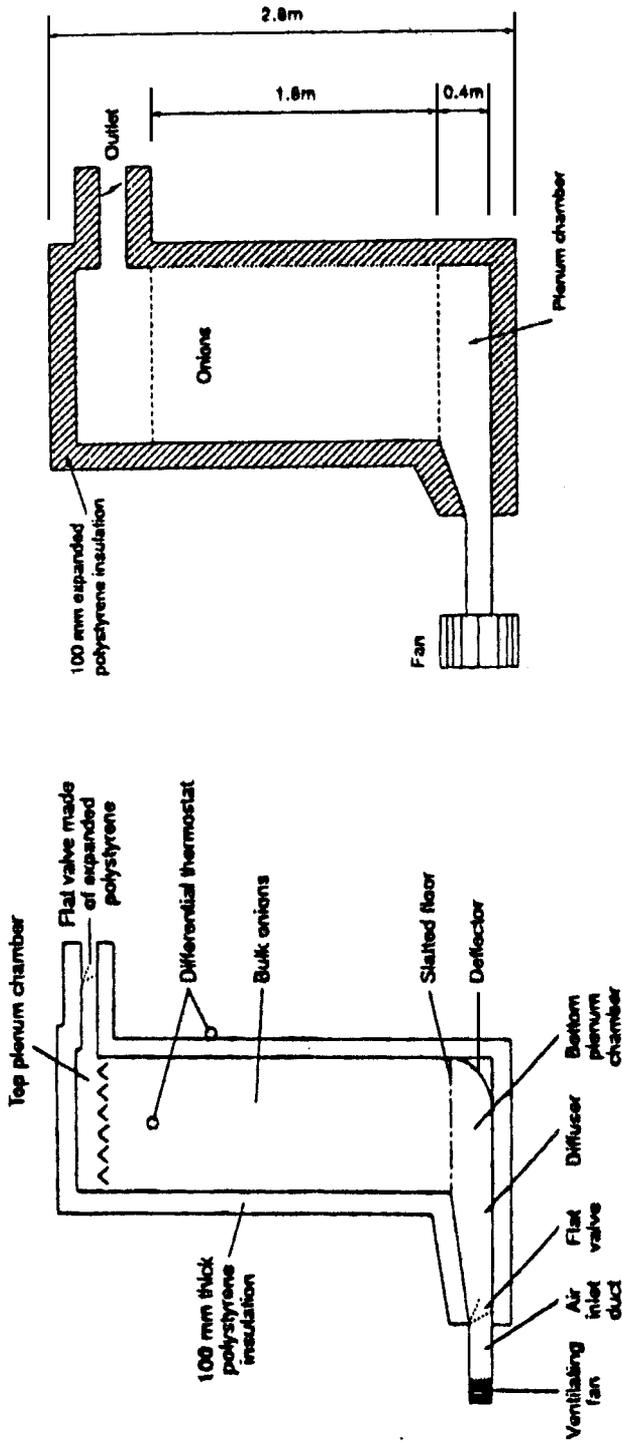


Figure 2.39. Typical night-ventilated onion store. (Sources: [5, 6, 9])

Table 2.19. Onion-bulb losses by storage method during 6 months' storage

Storage Method	Sound by Weight (%)	Rotting (%)	Sprouting (%)
Straw cottage ^a	43	22	7
Night-ventilated store ^b	58*	18 ^c	4*

Source: [16].

^a Average 36.1°C and 42% relative humidity.

^b Average 33.1°C and 60% relative humidity.

^c Not Significantly different at $P = .05$.

* Significantly different at $P = .01$.

2.3.9 Design and Operation of Onion Stores [15]

Design Objectives

The key objectives in the design of onion stores are to provide a structure that will protect the produce from environmental and physical hazards and contaminants; to facilitate handling, inspection, and stock control and provide safe working conditions; and to minimize fixed and operating costs. To achieve these objectives, decisions need to be made regarding store capacity and type of packaging (e.g., loose bulk versus bag), type of ventilation system (natural versus forced), and the appropriate storage-environment regime.

Determination of Store Capacity

The capacity of a store for onion storage depends on the type of packaging, which in turn affects the specific bulk volume of onions. The eaves height of the store is normally 1.5 m above the height of the crop. The range of specific bulk volume of onions and thermophysical properties that influence store design and bulb performance in storage are given in Table 2.20. The procedure for calculating the store capacity is as follows:

1. Using store dimensions available for storage, determine the volume of onions that can be filled: store length \times width \times desired depth of storage
2. Determine the quantity of onions capable of being held in store: volume of bulbs/specific volume

A common design problem is to calculate the size of store required to store a given quantity of bulbs. In this scenario, the following factors must be considered: volume of stored onions, additional space required for loading and unloading, space required for equipment to stand when the store is full, and the space taken up by ventilation ducts. In practice, the design of an onion store usually is based on a combination of factors that determine the feasibility of the store. Often, the resulting design is a compromise among many factors affecting size, location, type of packaging, and construction material. Based on the systems approach, flowcharts have been developed to assist in choosing between bag and bulk storage, and for selecting store size, type, location, and construction materials [15].

Table 2.20. Thermophysical properties of onions

Property	Value
Specific bulk volume	
Dry topped	1.9 m ³ ·ton ⁻¹ 2.25–2.5 m ³ ·ton ⁻¹
Wet untopped	2.9 m ³ ·ton ⁻¹
Bags	2.5–3.0 m ³ ·ton ⁻¹
Pallet-based bins	3.5–3.85 m ³ ·ton ⁻¹ 3.6–4.0 m ³ ·ton ⁻¹
Water content	
Dry	89.4%
Green	87.5%
Respiration heat	
0°C	9 W·ton ⁻¹
5°C	15 W·ton ⁻¹
10°C	21 W·ton ⁻¹
20°C	24 W·ton ⁻¹
Specific heat	3.77 kJ·kg ⁻¹
Freezing point	-0.8°C

Adapted from [15].

Design of Aeration Systems

The provision of adequate ventilation is critical to safe storage of onions, and the store should permit ventilation of the onions to remove the heat and moisture resulting from bulb respiration. Otherwise, the build-up of these products of respiration will lead to further increases in respiration and a rapid reduction of bulb quality. Often, the choice is between natural- or forced-ventilation systems. The fan delivery for pallet-based stores should be based on flow rate of 0.05 m³·s⁻¹·ton⁻¹ and static pressure of about 188 N·m⁻². The recommended airflow rates based on the direct harvest system practiced in the United Kingdom, where bulbs are harvested green and placed directly into store, are shown in Table 2.21.

Fans

Fans must be selected to provide adequate airflow rate against any backpressure in the store. They may be required to ventilate the entire store or an isolated area in the

Table 2.21. Recommended airflow rates based on the U.K. direct harvest system for onions

Crop	Stage I ^a		Stage II ^b		Cooling	
	Airflow (m ³ s ⁻¹ ton ⁻¹)	Pressure (kN·m ⁻²)	Airflow (m ³ s ⁻¹ ton ⁻¹)	Pressure (kN·m ⁻²)	Airflow (m ³ s ⁻¹ ton ⁻¹)	Pressure (kN·m ⁻²)
Field wilted	0.12	1–1.25	Not applicable	0.047	0.375	
Direct harvested	0.12	1–1.25	0.047	0.375	0.047	0.375

Source: [15].

^a Stage I, Initial drying of the bulb surfaces.

^b Stage II, Continued drying with skin curing and healing of the necks.

Table 2.22. Maximum permitted air velocities in ventilated systems

Location	Air Velocity ($\text{m}\cdot\text{s}^{-1}$)
Main duct	10
Lateral ducts	10
Inlet to fan house	5
Inlet to recirculation vents	5
Exhaust ventilator	5
Intake ventilator	7.5

Source: [15].

store. Fans should be capable of providing an airflow rate of $0.047 \text{ m}^3\cdot\text{s}^{-1}\cdot\text{ton}^{-1}$ of total store capacity against a back pressure of $375 \text{ N}\cdot\text{m}^{-2}$ (see Table 2.21). If rapid drying is required at the beginning of storage, this guideline also allows a higher airflow rate of $0.12 \text{ m}^3\cdot\text{s}^{-1}\cdot\text{ton}^{-1}$ to be applied against a back pressure of up to $1250 \text{ N}\cdot\text{m}^{-2}$ to one third of the store. In general, single axial-flow fans are used for most vegetable stores up to 200 ton, but in larger stores, a pair of matching axial fans are used, enabling the fan output to be matched to the area under ventilation.

Within the ventilation system, maximum air velocities exist at different locations (Table 2.22). The size of ducts and ventilators should be chosen to ensure that the maximum air velocities are not exceeded, and the cross-sectional area is calculated as the ratio of the total airflow ($\text{m}^3\cdot\text{s}^{-1}$) to the maximum permitted air velocity ($\text{m}\cdot\text{s}^{-1}$).

Main Ducts

These must be sized to meet the air delivery required but should not be less 1.3 m high and 0.8 m wide to allow access for the operator. Access doors should have minimum dimensions of $0.6 \text{ m} \times 0.9 \text{ m}$. The main ducts or plenum chambers must be capable of withstanding the forces exerted by the air, and the loads imposed by the onions, if used as a retaining wall. As a design guide, every $250 \text{ N}\cdot\text{m}^{-2}$ of air will exert $25.5 \text{ kg}\cdot\text{m}^{-2}$ force on the walls, with an additional $160 \text{ kg}\cdot\text{m}^{-2}$ lateral thrust for every meter depth of onions. Controlled roughening of the internal surfaces of the main duct will create sufficient turbulence to reduce the development of static pressure regain in the main duct.

Lateral Ducts

As with main ducts, these should be sized to ensure that air velocities do not exceed $10 \text{ m}\cdot\text{s}^{-1}$. Lateral ducts should be limited to 10 m in length, and typical cross-sectional areas for most root vegetables are 0.17 m^2 per meter length of lateral. Over 10 m length, lateral ducts should be tapered to increase the pressure further back along the lateral, thereby reducing the pressure gradient along the length. Table 2.23 gives a useful guide for determining the amount of tapering to reduce static pressure regain.

Positioning of Ventilators

To achieve maximum benefits, it is important that ventilators are well positioned to remove relatively high-temperature air (Fig. 2.40). High-level ventilators are more

Table 2.23. Tapering of laterals to reduce static pressure regain

Duct Length (m)	Ratio Cross-sectional Areas (inlet:outlet, m ²)
10	7:1
15	10:1
20	13:1

Source: [15].

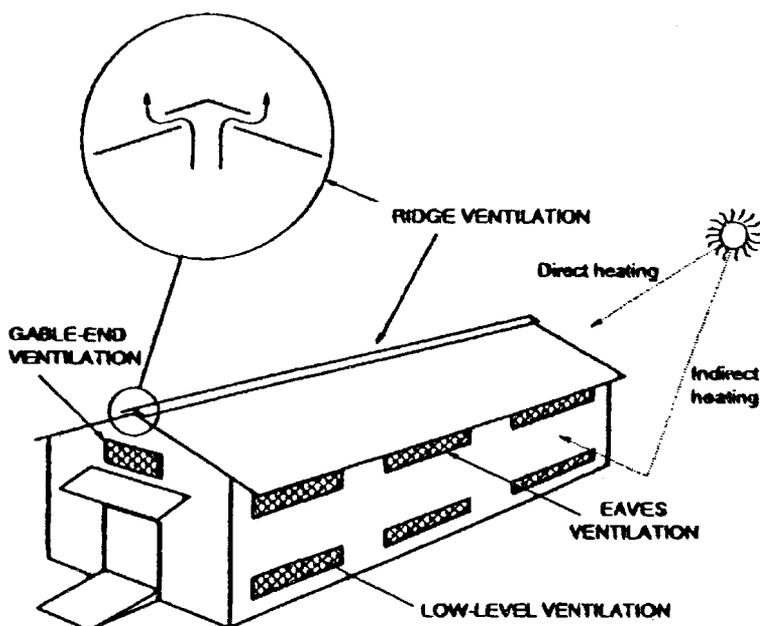


Figure 2.40. Positioning of ventilators within onion stores. (Source: [15])

effective than those positioned lower down, because warm air rises within the store. However, low-level ventilators will help to provide air movement throughout the store and stacked product if high-level ventilators are installed. Installing weld-wire mesh across all openings reduces security risk to product, and finer mesh should be used to exclude infestation by rodents and birds.

Systems Approach to Onion-store Management

The design and operation of efficient onion-storage system to maintain postharvest quality is often a compromise between optimum environmental requirements and the selection of store type, size, and location. A systems approach therefore is recommended to assist in the selection of appropriate storage systems based on a consideration of the

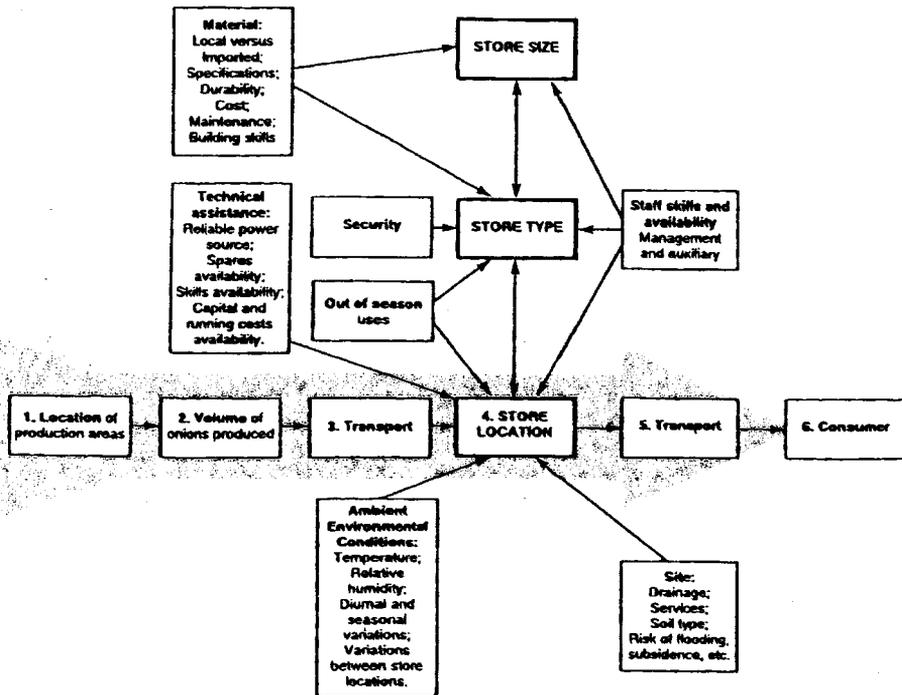


Figure 2.41. Decision tree for selection of store size, type, location, and materials for bulb onions. (Source: [15])

interrelated factors of environmental conditions, site, materials, technical assistance, and skills (Fig. 2.41).

References

1. Brewster, J. L. 1994. *Onions and Other Vegetable Alliums*. Wallingford, UK: CAB International.
2. Platt, B. S. 1962. Table of representative values of food commonly used in tropical countries. Medical Research Council, Special Report Series No. 302. London: HMSO.
3. FAO. 1972. *Food Composition Table for Use in East Asia*. Rome: Author.
4. Thompson, A. K., R. H. Booth, and F. J. Proctor. 1972. Onion storage in the tropics. *Tropical Science* 14(1):19–34.
5. *Report of the Steering Committee on Postharvest Food Losses in Developing Countries*. 1978. Washington DC: National Research Council, National Science Foundation.
6. Amuttiratana, D., and W. Passornisiri. 1992. *Postharvest Losses of Vegetables: A Report on Workshop Held Between 17 and 22 October at the Pakistan Agricultural*

- Research Council, Islamabad, Pakistan, ed. M. H. Bhatti, Ch. Hafeez, A. Jaggar, and Ch. M. Farooq. FAO Regional Co-operation for Vegetable Research and Development RAS/89/41.
7. van Kampen, J. 1970. The improvement of available onion varieties. *Zaadbelangen* 24:135–139.
 8. Woodman, R. M., and H. R. Barnell. 1937. The connection between the keeping quality of commercial varieties of onions and the rates of water loss during storage. *Ann. Appl. Biol.* 24:219–235.
 9. Foskett, R. L., and C. E. Petterson. 1950. Relation of dry matter content to storage quality of some onion varieties and hybrids. *Proc. Amer. Soc. Hort. Sci.* 55:314–318.
 10. Hanoaka, T., and K. Ito. 1957. Studies on the keeping quality of onions: I. Relation between the characters of the bulbs and their sprouting during storage. *J. Hort. Ass. Japan* 26:129–136.
 11. Magruder, R., R. E. Webster, H. A. Jones, T. E. Randall, G. B. Snyder, H. D. Brown, and L. R. Hawthorne. 1941. Storage qualities of principal varieties of American onions. US Dept. Agric., Circ. 619.
 12. Robinson, J. E., K. M. Brown, and W. G. Burton. 1975. Storage characteristics of some vegetables and soft fruits. *Ann. Appl. Biol.* 81:339.
 13. Oberbarnscheidt, B., B. Herold, and M. Geyer. 1996. Speisezwiebeln: Mechanisch belastet bei Ernte und Aufbereitung. *Gemüse* 32:492–496.
 14. Oberbarnscheidt, B., M. Geyer, and B. Herold. 1996. Einfluß mechanischer Belastungen auf Atmung und Masseverluste bei Speisezwiebeln. *Bornimer Agrartechnische Berichte* H.8.
 15. Brice, J., L. Currah, A. Malins, and R. Bancroft. 1997. *Onion Storage in the Tropics: A Practical Guide to Methods of Storage and Their Selection*. Chatham, UK: Natural Resources Institute.
 16. Thompson, A. K. 1996. *Postharvest Technology of Fruits and Vegetables*. London: Blackwell Science.
 17. Stow, J. P. 1975. Effects of humidity on losses of bulb onions (*Allium cepa*) stored at high temperature. *Experimental Agriculture* 11:81–87.
 18. Tindall, H. D. 1983. *Vegetables in The Tropics*. London: The McMillan Press.
 19. O'Connor, D. 1979. *Onion Storage: Grower Guide No. 2*. London: Grower Books.
 20. Rice, R. P., L. W. Rice, and H. D. Tindall. 1993. *Fruit and Vegetable Production in Warm Climates*. London: The MacMillan Press.
 21. Isenberg, F. M. 1955. The effects of height of fall on onion bruising. *Proc. Amer. Soc. Hort. Sci.* 66:331–333.
 22. Böttcher, H. 1996. *Frischhaltung und Lagerung von Gemüse*. Stuttgart: Eugen Ulmer.
 23. Currah, L., and F. J. Proctor. 1990. Onions in tropical regions. Natural Resources Institute Bulletin No. 35. Natural Resources Institute, Chatham, UK.
 24. KTBL. 1993. *Taschenbuch Gartenbau. Daten für die Betriebskalkulation*. 4. Auflage, Münster Hilstrup.

25. Karmarkar, D. V., and B. M. Joshi. 1941. Investigations on the storage of onions. *Indian Journal of Agricultural Science* 11:82–94.
26. Kapur, N. S., P. B. Mathur, and K. K. Singh. 1953. Cold storage of onions. *Indian Journal of Horticulture* 10:9–38.
27. de Visser, C. L. M. 1993. Teelt van Zaauijen. Proefstation en Informatie—en Kenniscentrum voor de Akkerbouw en de Groenteteelt in de Vollegrond, Lelystad, Teelthandleiding nr. 52.
28. Thompson, A. K. 1982. The storage and handling of onions. Report of the Tropical Products Institute, G160. Chatham, UK.
29. Bleasdale, J. K. A., G. W. Tucker, and K. Hough. 1969. Bulb storage of onions, onion skins colour and keeping quality. In *National Vegetable Research Station Annual Report*, pp. 78–79. UK.
30. SeaLand. 1991. *Shipping Guide to Perishables*. Iselin, NJ: SeaLand Service.
31. Hardenburg, R. E., A. E. Watada, and C. Y. Wang. 1990. The commercial storage of fruits, vegetables and florist and nursery stocks. USDA, ARS, Agriculture HandBook 66.
32. Smittle, D. A. 1989. Controlled atmosphere storage of Vidalia onions. In *International Controlled Atmosphere Conference 5th Proceedings*, Wenatchee, Washington, USA, vol. 2.
33. Smittle, D. A. 1988. Evaluation of storage methods for “Granex” onions. *J. Amer. Soc. Hort. Sci.* 113:877–880.
34. Chachin, K., and K. Ogata. 1971. Effects of delay between harvest and irradiation and storage temperatures on the sprout inhibition of onions by gamma radiation. *J. Food Sci. Technol. (Japan)* 18:378.
35. Maude, R. B., and A. H. Presley. 1977. Neck rot (*Botrytis allii*) of bulb onions: 1. Seed-borne infection and its relationship to the disease in the onion crop. 2. Seed-borne infection in relationship to the disease in store and the effect of seed treatment. *Ann. Appl. Biol.* 86:163–180, 181–188.
36. Bengtsson, L. L., and J. H. Whitaker, eds. 1988. Farm structures in tropical climates: A textbook for structural engineering and design. In *FAO/SIDA Co-operative Programme: Rural Structures in East and South-East Africa*. pp. 248–249. Rome: FAO.
37. Shukla, G. S., and R. K. Gupta. 1994. Development and evaluation of concentric-type storage structures for onions. Alliums for the Tropics. *Acta Horticulturae* 358:389–394.
38. Gray Grain. 1988. *Onion Drier*. UK: Author.
39. Skultab, K., and A. K. Thompson. 1992. Design of a night ventilated onion store for the tropics. *Agricultural Mechanisation in Asia, Africa and Latin America* 23(1):51–55.
40. Hruschka, H. W. 1974. Storage and shelf life of packaged green onions. United States Department of Agriculture, Market Research Report 1974.
41. Scholz, E. W., H. B. Johnson, and W. R. Buford. 1963. Heat evaluation rates of some Texas-grown fruits and vegetables. *Journal of the Rio Grande Valley Horticultural Society* 17:170–175.

2.4 Cassava Storage

Linus U. Opara

2.4.1 General

Terminology

Cassava (*Manihot esculenta* Crantz) also is called *yuc(c)a* (Spanish), *mandioca* (Portuguese), *tapioca*, *manioc* (French), and *ketella*, *ubi kayu*, or *kaspe* in Indonesia. Cassava belongs to the family *Euphorbiaceae*. Many varieties are cultivated in the tropics, including improved high-yield cultivars developed at the International Institute for Tropical Agriculture in Nigeria, Centro Internacional de Agricultura Tropical in Colombia, and other research centers. Several varieties of cassava are cultivated in many parts of the world, and these can be classified into two groups (sweet and bitter) based on the linamarin content of the roots [1]. In practice, the difference between the two groups is often obscure. Each cassava stem usually bears multiple tubers (Fig. 2.42).

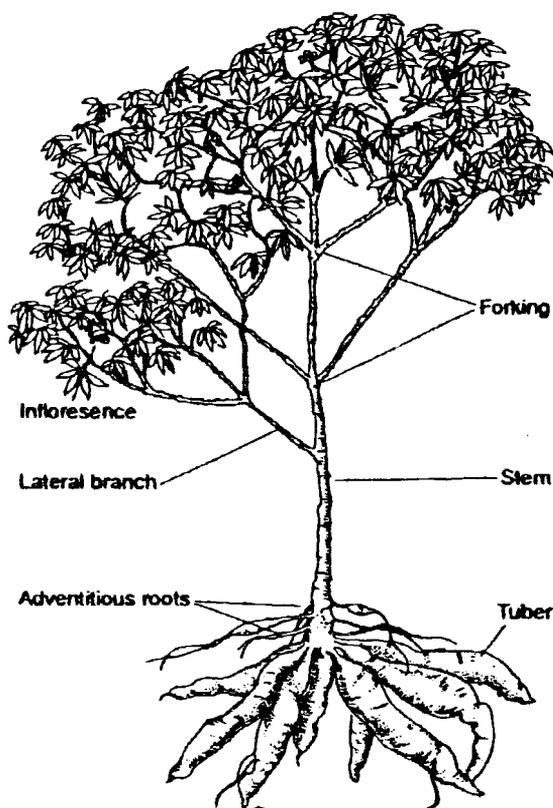


Figure 2.42. Cassava plant morphology showing tubers.

Economic Importance

Cassava originated in Latin America and is now cultivated in almost all parts of the world. Total world cultivated area is about 15.76 million ha, of which 9.30 million ha are in Africa and 3.79 million ha in Asia. In the early 1990s, world production of cassava was approximately 140 million ton, and the top producers were Brazil, Thailand, Zaire, Nigeria, Indonesia, Tanzania, Uganda, India, Paraguay, and Mozambique. Current global annual production is estimated to be over 152.22 million ton, of which about 46.28% is produced in Africa, 33.66% in Asia, and 19.28% in South America. Average annual world yield has been estimated to be 9.66 ton·ha⁻¹, and experimental yields of over 60 ton·ha⁻¹ have been recorded [2].

During the period from 1988 through 1990, developing countries produced 149 million ton of cassava, and between 1961 and 1988 production increased by 100%. Also, during the period from 1961 through 1988, the area in cassava production increased by about 50%, and yields increased by 32% [3]. During the past four decades, the output of cassava has grown much faster in Africa than in the other major producing regions, due mainly to increases in cultivated area (Table 2.24).

Cassava ranks as the most important root crop in terms of world production, ahead of the sweet potato. It is also the most important root crop in most tropical countries and provides the major source of dietary calories for about 500 million people in many developing countries in Africa, Latin America, and Asia. The roots are used as food for humans and livestock, and leaves of many cultivars are used as vegetable. Many

Table 2.24. Cassava production, area, and yield in developing countries

	Total	Sub-saharan Africa ^a	Asia ^b	Latin America ^c
1988–1990				
Production (×1000 ton)	149,193	65,344	52,836	31,013
Area (×1000 ha)	15,074	8,440	4,013	2,621
Yield (ton·ha ⁻¹)	9.9	7.7	13.2	11.8
Changes in production				
1973–75 vs. 1961–63	41.2	35.2	61.4	33.4
1988–90 vs. 1973–75	41.3	49.6	74.7	–2.1
1988–90 vs. 1961–63	99.5	102.3	181.8	30.6
Changes in area				
1973–75 vs. 1961–63	28.4	25.3	27.0	39.1
1988–90 vs. 1973–75	17.8	18.4	36.5	–3.7
1988–90 vs. 1961–63	51.3	48.3	73.4	33.9
Changes in yield				
1973–75 vs. 1961–63	9.9	7.9	27.1	–4.1
1988–90 vs. 1973–75	19.9	26.4	27.9	1.7
1988–90 vs. 1961–63	31.8	36.4	62.6	–2.5

Source: [3].

^a Not including Algeria, Egypt, Libya, Morocco, Tunisia, and South Africa.

^b Not including Israel and Japan but including Oceania (except Australia and New Zealand).

^c Including Central, North (except Canada and the United States), and South America.

cultivars can be cooked and eaten fresh or processed into secondary food products. Industrial uses of cassava includes starch extraction and incorporation into animal feeds. Cassava is an important export commodity in some countries, such as Thailand, where it is grown mainly for export in processed products. In Africa, cassava is important not just as a subsistence or food-security crop but also as a major source of income for producing households [4, 5]. It is grown in every country on the continent, but cultivation is concentrated in the humid tropical regions. Annual production in Africa is about 48 million ton, and this translates into an estimated average of more than 200 cal per day for 200 million people [6]. In parts of Central Africa, cassava constitutes over 50% of the average staple food consumed.

The nutritional value of cassava is important in the diets of many rural and urban areas in the tropics, especially in Africa, Asia, and Latin America. It is estimated that the crop provides about 40% of all calorie intake in Africa [7]. In general, cassava often has been considered an inferior food in many parts of the world because the fresh tuber has a high carbohydrate content (35%) but is low in crude protein (<2%) and essential minerals and vitamins, and even potentially toxic [8, 9]. The leaves also are consumed as a vegetable, and they provide a good source of protein and essential nutrients. In many parts of sub-Saharan Africa in particular, cassava is the major food source, especially where drought and lack of good agronomic inputs preclude the cultivation of other crops. In marginal agricultural lands, the carbohydrate yields of cassava are high compared with other crops.

Postharvest losses are high because cassava roots are extremely perishable once detached from the plant material. This can be attributed to their high moisture content (50% to 70%) and high respiratory rate, because the resultant heat production softens the tissue. These physiological changes (see Section 2.1) lead to deterioration, and subsequently rot and decay may occur. Mechanical damage during harvesting and postharvest handling provides an avenue for microbial infection of tubers and thereby renders the crop unsuited for long-term storage. Postharvest losses also can result from specific infection by fungi and bacteria, which cause decay of cassava tubers [10], and from attacks by rodents, insects, and nematodes. Inadequate storage structures can result in substantial losses due to high weight loss and microbial infection (Table 2.25).

Table 2.25. Cassava weight losses after 25 days in different storage structures

Type of Structure	Weight Loss by Decay and Shrinkage (%)
Permanent building	98.7
Dark room wooden building	86.8
Local building	92.2
Pit	64.0
Trench	91.1

Source: [11].

Cassava roots are particularly more perishable than other tuber crops because they do not exhibit endogenous dormancy (see Section 2.5), have no function in propagation, and possess no bud primordia from which regrowth can occur [12, 13]. Food and Agricultural Organisation (FAO) surveys estimate that losses of cassava roots in Brazil, Indonesia, and the Dominican Republic were 10%, 10%, and 24.4%, respectively. Studies in the Dominican Republic estimate that 17.4% of the cassava root marketed fresh was lost before it could be consumed, although it remained only 1 or 2 days at the wholesale level of the market chain [14]. In 1978, it was estimated that global postharvest losses of cassava amounted to 10% of production [15]. Despite the predominant position of cassava among all other root and tuber crops, the poor postharvest storage life is a major economic constraint in its utilization.

2.4.2 Maturity, Harvesting, and Yield

Root Maturity

The maturity of cassava roots varies among the different cultivars. In general, the roots mature in 9 to 24 months after planting. Some low-yielding, quick-ripening varieties can be harvested a period of 6 months after planting. Mature cassava roots can be harvested year-round. During the growing season, both root and starch production increase rapidly to their maximum value, and they decline afterwards. Where possible, harvesting should be timed to correspond with the period of maximum value of the desired root attribute. Leaving the roots in the ground for too long could lead to lignification, which manifests in a tough, woody tissue.

Harvesting

Harvesting usually is carried out manually by digging around the roots, plucking the roots individually, or lifting the entire bunch attached to the stem. In light soils, the entire root can be lifted by pulling the stem. In some places, the stalks are cut 40 to 50 cm aboveground by hand or machine the day before harvest. Planting material for the next season is selected and the rest is burned. Cassava roots are highly perishable, and harvesting must be carried out carefully to avoid damage to the roots.

In some parts of southeastern Nigeria where food supply is inadequate and cassava is the main crop, some rural farmers harvest their crop twice. In this situation, the first harvest is often after the rainy season. A modified form of double harvesting also is adopted by some farmers to ensure that good-quality planting materials are left intact until the beginning of the next growing season. Many experimental designs of mechanical harvesting devices have been developed [16], but these have limited application for most of the rural subsistence farmers who cultivate a large proportion of the total production. In many cassava-growing areas, the leaves are harvested as a source of food and cash. Multiple harvesting up to twice per week has been reported [17], but this practice could adversely affect root yields due to decreased photosynthetic activity.

Root Yield

Root yields are variable depending on a combination of genetic, environmental, maturity, and crop-management factors. Improved varieties can yield 1.5 times more than

Table 2.26. Yield components of cassava in Nigeria

	Fresh Root (ton·ha ⁻¹)	Plant Density (stand·ha ⁻¹)	Average Root Weight (kg)	Roots per Plant	Harvest Index
Improved Variety					
Minimum	3.20	1250	0.09	3.15	0.30
Mean	19.44	9595	0.45	6.17	0.59
Maximum	36.00	20000	1.14	35.68	0.89
SD	8.32	4702.92	0.23	5.49	0.14
N	34	34	34	34	34
Local Variety					
Minimum	1.25	1250	0.05	0.37	0.32
Mean	13.41	10586	0.38	4.03	0.56
Maximum	74.10	41250	1.69	12.19	0.89
SD	10.02	5170.50	0.25	2.01	0.13
N	105	105	105	105	105

Source: [5].

local varieties (Table 2.26). Between 10 and 24 months after planting, yields up to 11.0 to 17.0 ton·ha⁻¹ and 17.0 to 19.0 ton·ha⁻¹ are possible with local and improved varieties, respectively [5]. The improved varieties also have better yields than the local varieties in an intercropping pattern commonly practiced in many tropical developing countries. The yield of sole-cropped improved varieties (23 ton·ha⁻¹) was 40% higher than crops grown under an intercropping pattern as major crops (16.6 ton·ha⁻¹), and nearly 95% higher than when they were grown as minor crops (12.1 ton·ha⁻¹). Yields among the world's major producing regions are shown in Table 2.24.

2.4.3 Handling, Curing, and Packaging

Cassava roots, especially the “sweet” types, are highly susceptible to physical injury such as bruising. Bruised tissue turns greyish. In addition to the downgrading of roots, bruising accelerates physiological deterioration and also provides an avenue for opportunistic infection with decay-causing microbial agents. To reduce impact and compression damage, roots should be harvested with 2 to 3 cm of stem attached. Careful handling of roots also is required.

Curing refers to the process of wound healing with the development and suberization of new epidermal tissue called *periderm*. Cassava roots are cured at high humidity levels to improve potential storage life. The recommended conditions are 30 to 40°C and 90% to 95% relative humidity for 2 to 5 days [18].

For long-distance transportation, roots should be packaged adequately for ease of handling and to reduce the incidence of damage. Full-telescopic fiberboard boxes, 23 kg with excelsior or paper wrapping and padding, should be used where they are available [19]. Packaging in moist materials such as sawdust or in wooden boxes allows curing and storage of fresh cassava roots for 1 to 2 months [20]. Only roots in top quality condition should be packaged and stored. Desirable attributes include thick root, brown

skin, white flesh, and root length of 15.9 to 25.0 cm. Roots in top-quality condition have a longer storage and shelf life and therefore allow more time for transportation, storage, and marketing.

2.4.4 Storage Environment Requirements

Storage of Fresh Root

Fresh cassava roots are highly perishable and can suffer serious physiological deterioration within 24 hours after harvest. The common practice in most producing areas is to consume them close to the place of production by selling or processing the harvested roots immediately. Fresh cassava roots can be stored in the ground by delaying harvest of mature crop until needed. When mature roots are left in the ground, the older roots tend to become fibrous and woody [20]. Roots also can be harvested and reburied in a cool place for short storage or held in modified environments in specially built storage structures. A moist storage environment is essential to control primary deterioration [21, 22]. Delaying harvest provides long-term storage, because postharvest storage of fresh cassava often is a short-term strategy due to its highly perishable nature.

Storage at ambient conditions is the most widely practiced for cassava roots. However, these conditions promote rapid deterioration of roots, and several postharvest treatments have been recommended to prolong storage life and minimize the incidence of diseases and disorders.

Cassava roots store fairly well under refrigeration. Cassava is the only root that tolerates low temperatures and can be stored at 0 to 2°C for up to 6 months [23]. The roots will last for 1 to 2 weeks at 5.5 to 7°C and 85% to 90% relative humidity in storage. Storage at 20°C and above with high humidity results in large losses. Several combinations of storage temperature and relative humidity have been recommended (Table 2.27). The optimum storage requirement depends on variety, climatic conditions,

Table 2.27. Recommended storage conditions for cassava (*Manihot esculenta*)

Temperature (°C)	Relative Humidity (%)	Storage Life
0	85	23 wk
0–2	85–90	5–6 mo
0–2	85–90	Several mo
0–5	85–90	1–2 mo
0–5	85–95	≤6 mo
1	90	5–6 mo
5–8	80–90	2–4 wk
10	90–95	10–14 d
13–14	—	9 d
20	60	2–4 wk

Sources: [18, 24–30].

and incidence of mechanical damage during harvesting and handling operations. A beneficial effect of refrigerated storage is to slow down the physiological and pathological processes that lead to deterioration, and losses include visual and organoleptic quality attributes. For most cultivars, the roots store well at 0 to 5°C with 85% to 90% relative humidity [31, 32]. Storage at 3°C created losses of 6% to 7% per week, while storage at 1.7 to 3.3°C and 80% to 90% relative humidity for 2 weeks resulted in an 11% loss. Stored roots also had internal browning and mold growth [33]. Precooling of roots by hydrocooling or forced air is recommended for refrigerated long-term storage. Cassava is not susceptible to chilling injury as are other tropical root crops if held at too low a temperature [34].

Storage of Processed Cassava Products

Adequately dried products can be stored up to 3 to 6 months provided insect infestation is controlled [31]. The storage life and keeping quality depend on the moisture content of the product. For dried chips, the moisture content normally should be less than 14%, and polythene-lined jute bags can be used successfully to store the chips. For cassava flour, it is advisable to store dried chips and mill them when flour is required. The milled product then can be stored in thick-gauge airtight plastic bags. Moisture and insect ingress into the package must be prevented.

2.4.5 Postharvest Treatments

Treatment of freshly harvested roots with sodium hypochlorite, or dipping in fungicides such as benomyl or Thiabendazole, and packing them in plastic reduces the development of storage rots and decay [35]. Cassava roots also can be stored in good condition for 1 to 2 months at ambient room temperature following coating with paraffin wax [36]. This wax treatment is applied on roots destined for export market in some parts of the Latin America. Both hot-air and hot-water treatment of roots minimize the incidence of vascular streaking during storage [37]. Modified atmosphere packaging of cassava roots with polyethylene bags at ambient conditions can be useful to maintain their freshness for several weeks [38, 39].

2.4.6 Storage Disorders and Diseases

Cassava is susceptible to several pre- and postharvest disorders, pests, and diseases. Well-illustrated texts devoted to the problems of field and postharvest diseases and disorders of cassava are available [25, 40]. Fungal root rot is a major cause of both pre- and postharvest microbial deterioration, but bacterial soft rot also is quite common. There are three principal types of preharvest root rots: generalized pungent soft rot caused by *Phytophthora* spp., generalized nonpungent rot caused by *Pythium* spp., and localized rot caused by smallpox root disease. The most common problems in stored cassava roots are rots and vascular streaking.

Vascular streaking, also described as “blue vein” [41], results from physiological deterioration and is followed by secondary microbial rotting. Physiological deterioration

manifests as soft deterioration or fermentation, with brown streaking of the vascular strands; microbial deterioration of cassava roots manifests as circular, dry deterioration, with brownish-black streaking of the vascular strands.

Cassava-root rot is encouraged by warm moist conditions and poor ventilation. Vascular streaking occurs as a result of stress produced by high rates of water loss from physical injury [42, 43]. The onset of root deterioration is accompanied by increases in respiration and ethylene production [44]. The culinary and taste qualities of affected roots are adversely impaired. Susceptibility to vascular streaking varies considerable among cultivars [45].

Postharvest rots and decay can be controlled by low-temperature storage or by fungicide treatment applied immediately after harvest [46]. If the responsible fungus is tolerant to low temperatures, postharvest fungicide treatment offers the principal control strategy [47, 48]. Discoloration of roots due to vascular streaking can be inhibited by heating the roots for a short period of time prior to storage, or by hot-water immersion [37]. Postharvest treatments and storage practices that minimise moisture loss, such as curing, waxing, cold storage, and high-humidity modified atmosphere packaging (MAP) are beneficial in reducing the development of vascular streaking. Coating the roots with a paste of earth and mud can preserve their freshness for periods of 4 to 6 days. Gamma irradiation of roots also can be beneficial [49].

Preharvest practices such as drastically pruning the aerial parts of the plant 2 to 3 weeks prior to harvest prolongs the storage life of roots and thereby reduces the susceptibility of roots to vascular streaking [23, 37]. Where this is practiced, it is recommended that a short “stub” of stem be left intact with the harvested roots to avoid cutting the roots and to minimize postharvest handling and the associated physical damage. To minimize root rot, preplanting and prestorage treatment of cassava stake with different chemical formulations has been recommended (Table 2.28).

Table 2.28. Chemical formulae suggested for stake treatment before planting and storage

	Trade Name	Common Name	Parts per Million	Amount of Commercial Product per Liter of Water
Formula no. 1	Dithane M-22	Maneb	—	2.22 g
	Antracol	Propineb	—	1.25 g
	Vitigran 35%	Copper oxychloride	—	2.00 g
	Malathion W.P. 4%	Malation ^a	—	5.00 g
Formula no. 2	Malathion E.C. 57%	Malathion E.C.	1000	1.5 cm ³
	Bavistin W.P. 50%	Carbendazim	3000	6 g
	Prthocide W.P. 50%	Captan	3000	6 g
Formula no. 3	Orthocide W.P. 50%	Captan	3000	6 g
	Bavistin W.P. 50%	Carbendazim	3000	6 g
	Aldrin 2.5%	Aldrin	—	1 g/stake

Source: [40].

Note: 1000 ppm = 1 g per liter of active ingredient of the product.

^a With E.C. 57% use 1.5 cm³.

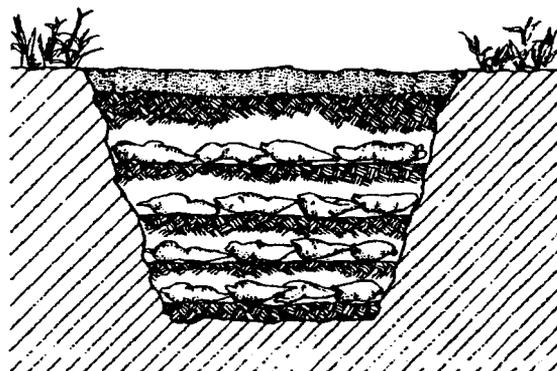


Figure 2.43. Cassava stored in trench with complete soil cover.

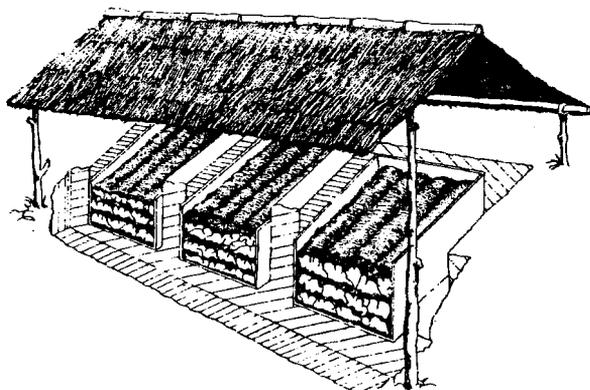


Figure 2.44. Fully filled trench under thatch shed.

2.4.7 Types of Storage Structures

Traditional Structures

Burying harvested roots underground is a common storage method. Roots also are piled in heaps and watered daily to keep fresh. Several types of storage structures have been used, ranging from pit and trench (Fig. 2.43) to bamboo-thatch room (Fig. 2.44) and permanent building. Weight loss and microbial losses are high in these structures (see Table 2.25), due to poor environmental control.

Improved Storage Structures

Several structures and methods have been utilized to improve the storage life and minimize spoilage of cassava roots. Two low-cost structures that can be implemented successfully by farmers and processors [50] are: trenches and boxes containing sawdust (Fig. 2.45). In either structure it is recommended that cassava roots should be harvested undamaged with about 14 to 20 cm of stem attached. Roots in sawdust storage should

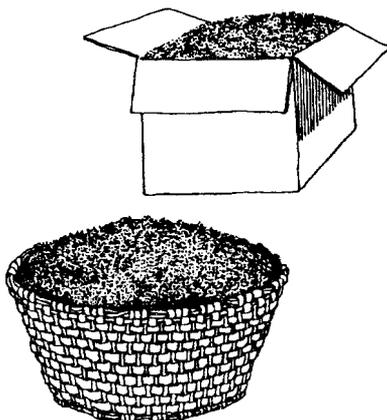


Figure 2.45. Boxes containing sawdust for cassava storage.

be inspected every 3 days to ensure that sawdust is kept moist, while the top soil layer of the trenches should be moistened regularly once a week with clean water. In either structure cassava roots can be successfully stored for 6 to 8 weeks. If large quantities of cassava roots need to be stored, it is economical to make several trenches under the same shed. Details of the construction materials and storage procedure can be found in refs. [49] and [50].

“Damp storage” structures developed by Centro Internacional de Agricultura Tropical also have given good storage results, especially for small farmers. A pile of roots is covered by straw and then soil, and ventilators then are used to reduce temperature in the pile during the hot dry season. The damp condition in the pile enables 75% of the root to be stored for a month or more [17].

2.4.8 Agroprocessing of Cassava Roots

Agroprocessing of cassava roots is necessary to produce staple products and industrial raw materials (Fig. 2.46). As part of the postharvest food chain, the primary objectives of cassava processing are to circumvent poor storage, eliminate undesirable constituents (mainly cyanide), and improve organoleptic properties. Cassava is processed and eaten in many forms: boiled as a vegetable; sliced, dried, and milled into flour; or grated and garified to produce gari, which is the most popular cassava product in West Africa. Many other food products are made from cassava roots, but the principal products are cassava flour and gari. The cooking and processing operations are necessary to reduce the toxicity due to naturally occurring cyanide (prussic acid), which is produced following the rupture of the cells of root tissue.

The traditional methods of gari and cassava-flour preparation are shown in Fig 2.47. In gari production, freshly harvested cassava is peeled, washed, grated, and allowed to ferment for 4 days, after which the pulp is sieved and roasted in a pan to a moisture

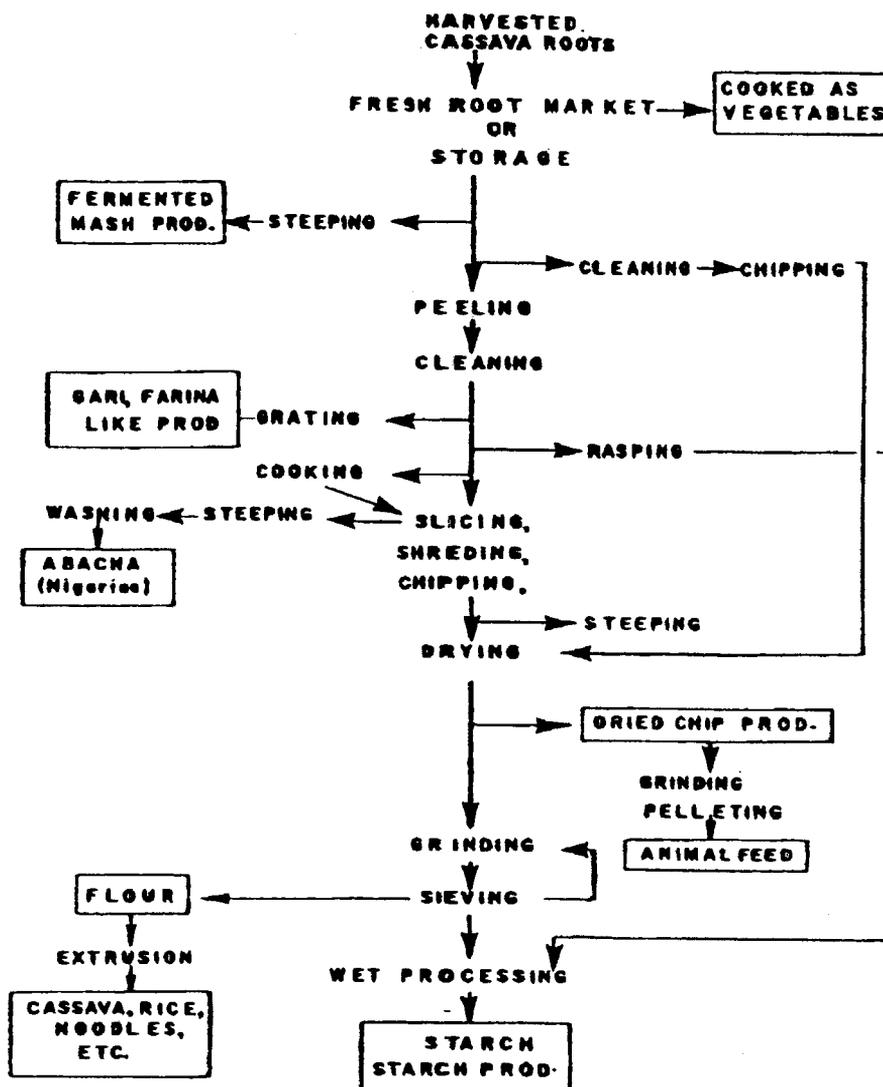


Figure 2.46. Flowchart for agroprocessing of cassava into food products and raw materials.

content of about 10.5%. In general, gari yield is about 25% by weight of the unpeeled roots. In cassava-flour production, the tubers are peeled, sliced, soaked for 24 hours, and dried in the sun for 7 days to a moisture content of about 12%. In general, the drying is carried out in the sun or in the oven until the moisture content is reduced from 60% or 70% down to 10% to 14% [51]. The dried cassava slices are then dry-milled and bagged.

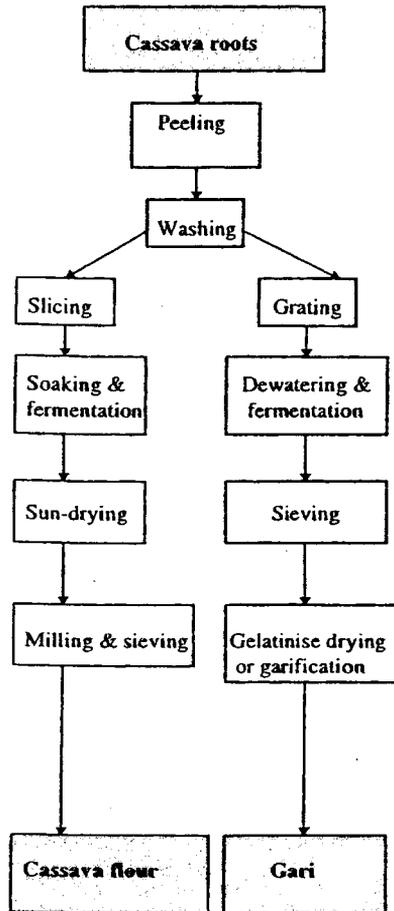


Figure 2.47. Traditional processes for production of cassava flour and gari.

Peeling is a critical unit operation in cassava processing because of its role in detoxification of the root. The average hand-peeling rate is about 25 kg per hour, with a loss of about 25% to 30%. The loss is higher (30%–40%) with mechanized peeling with a hand-trimming system. Because cassava root is made up of about 15% peel, with a total cyanide content of about $950 \text{ mg}\cdot\text{kg}^{-1}$ (fresh-weight basis) in the peel and $35 \text{ mg}\cdot\text{kg}^{-1}$ in the flesh, peeling alone removes about 83% of the total cyanide content. Peeling (including the cork layer) accounts for 10% to 20% of the total weight of roots.

The principal nonfood products made from cassava roots are industrial starch and chips for animal feed. The characteristics of cassava starch and its derivatives make it suitable for application in many industries including textiles, paper, pharmaceuticals,

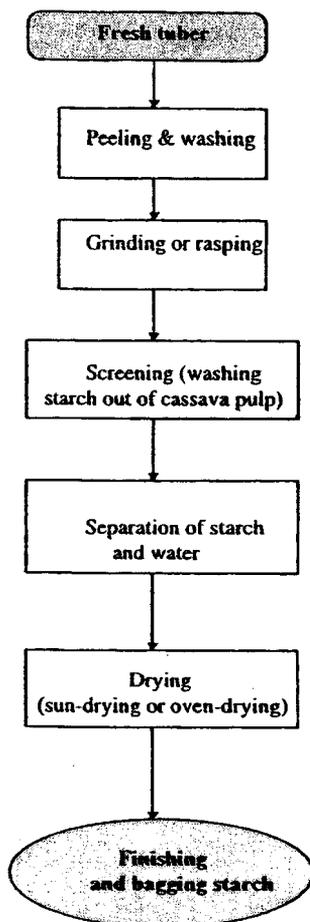


Figure 2.48. Unit operations for production of cassava starch.

and manufacture of batteries. Cassava flour can substitute for up to 10% to 30% of wheat flour in bread. This is of particular interest because the nearly zero fat content enhances storage life of the product. Cassava flour is also a good substitute for cereals in broiler chicken rations at levels as high as 70%, and layers can be fed up to 50% cassava meal, provided that their diets are well balanced in other nutrients [49]. In swine production, the digestibility of cassava-based diets is equivalent to or even better than cereal-based formulations.

The principal operations in starch production from cassava roots are shown in Fig. 2.48. Prior to drying, the starch collected from the sediment tanks contains about 45% to 50% moisture, and this needs to be dried to 10% to 13% for safe long-term storage.

Evaporative drying in the open air or in ovens is preferred. During sun drying, 1 to 2 days will be sufficient in the dry season to reduce the moisture content to a safe level. If oven drying is used, the drying temperature should be kept below the gelatinization temperature of starch granules. Normally, a drying temperature of 50 to 60°C is sufficient. A summary of the mass balance at each processing stage for gari production is shown in Fig. 2.49.

Considerable success has been achieved in various cassava-growing areas in the mechanization of processing operations for gari and flour production. Commercially available machinery and processing techniques are well documented for both rural and industrial processing [3, 9, 16, 17, 52, 53], including cost estimates [49]. Typical equipment used for gari production, from tuber peeling to garification, are shown in Figs. 2.50 and 2.51.

2.4.9 Nutritional and Engineering Properties

Nutritional Properties

Cassava root is a good energy source, containing high quantities of carbohydrate and water. Contents of protein and minerals are small (Table 2.29); dry-matter content of the fresh root is about 40%.

Physicochemical Composition

Cassava tubers consist of a fibrous peel (10%–15% of tuber weight) and a core (Fig. 2.52) which is the main storage region for starch. The peel has only about 50% the starch content of the core (Fig. 2.53). Cassava contains two cyanogenic glucosides (linamarin and lotaustralin), which upon hydrolysis produce the very toxic cyanide. Linamarin is present in much larger quantities, usually up to 90% of the total [57], and the normal cyanogen content of cassava roots varies between 15 and 400 mg HCN per kilogram fresh weight [58]. Variety and environmental and cultivation practices affect the concentration in roots, and there is also considerable variation in the distribution of the glucosides within the single root. The cyanogenic glucosides increase from the center of the tuber outward, with the highest HCN content in the peel [59]. The presence of residual cyanide in improperly processed cassava foods contributes to the development of goiter and spastic paraparesis, which are endemic in several regions in Africa [7]. The leaves generally contain 5 to 10 times more cyanide than the tubers. The cyanide content can be established only by chemical analysis of the leaf or tuber [1, 60], and not by any particular morphological or organoleptic attributes.

In addition to the nutritional and antinutritional properties of starch, there are some physicochemical characteristics of cassava roots that are relevant to the identification of processing and value adding. These are summarized in Table 2.30.

Thermophysical and Rheological Properties

The thermophysical and rheological properties of cassava root affect the utilization and options in processing. The principal properties in this regard are starch-grain size, starch-extraction rate, viscosity, and gelatinization temperature (Table 2.31).

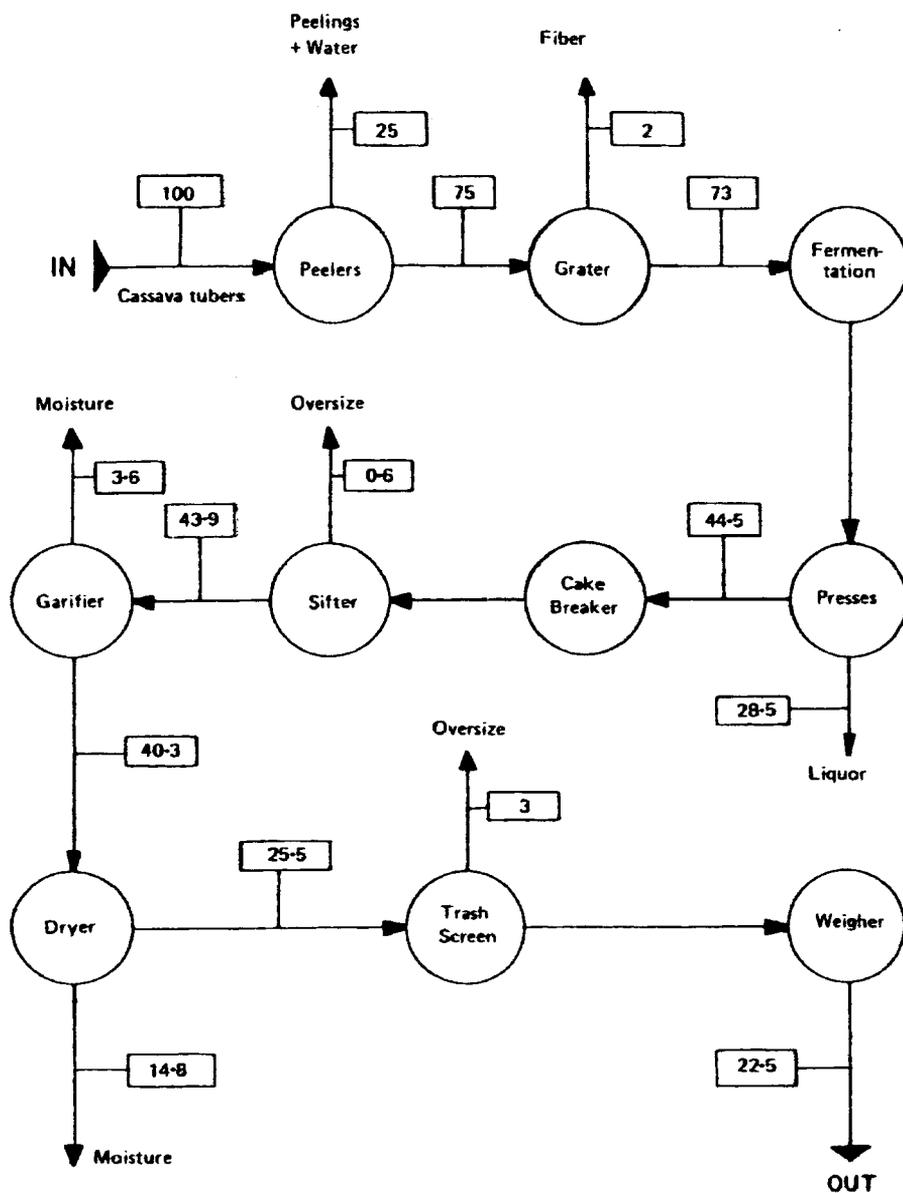


Figure 2.49. Mass balance for production of gari.

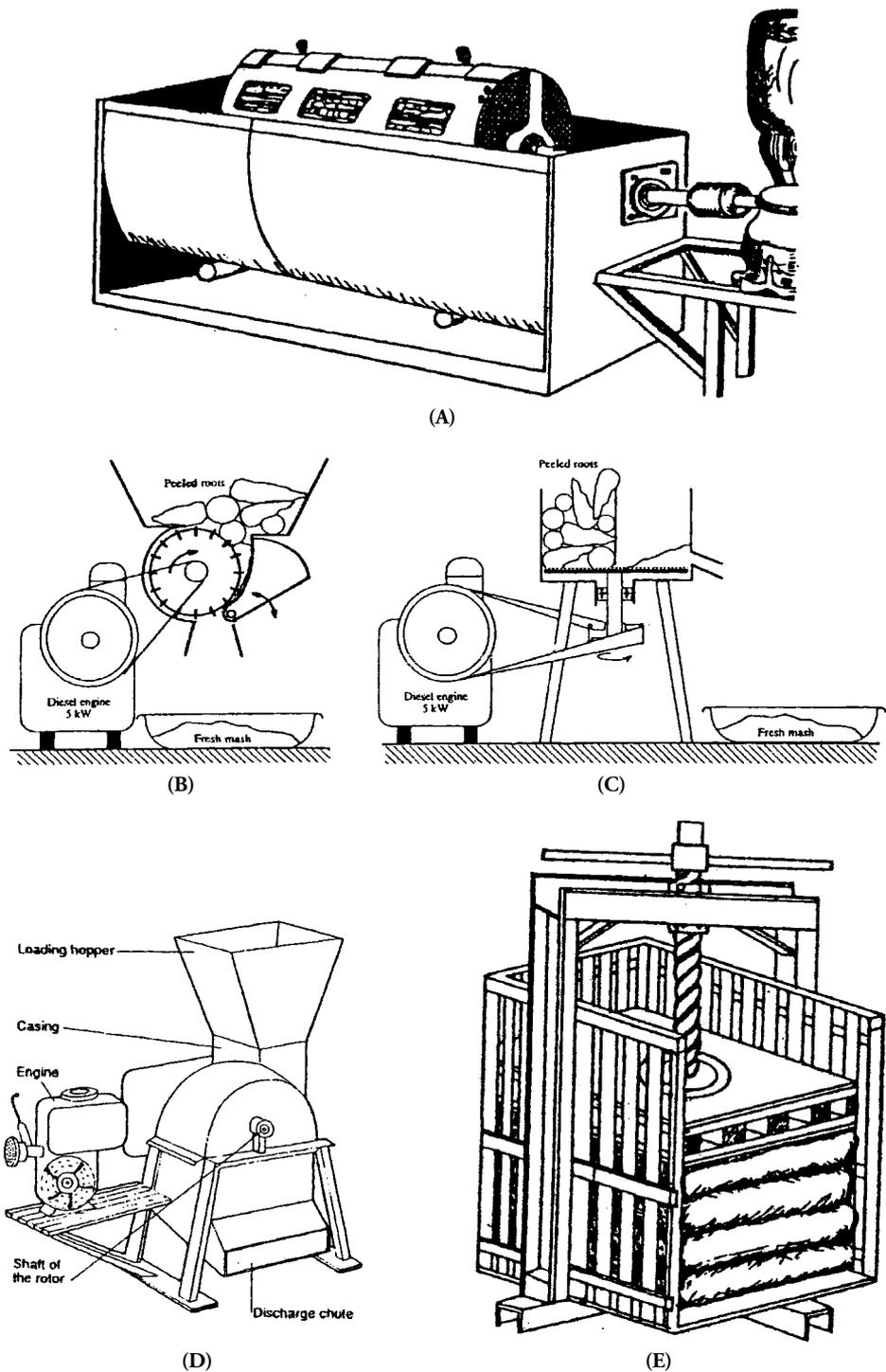
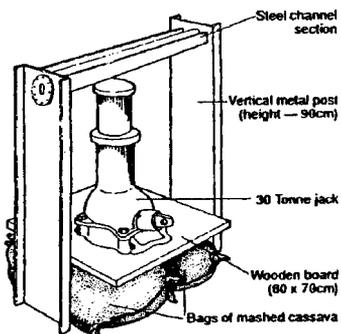
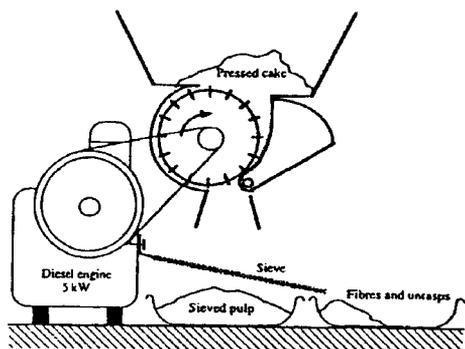
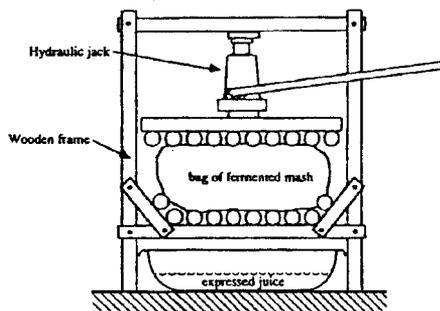


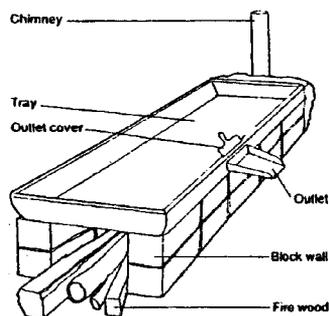
Figure 2.50. Various equipment used for gari production. A, cassava peeler and washer; B, saw-blade drum grater; C, vertical shaft plate grater; D, typical cassava grater; E, screw-type cassava mash press. (Sources: [49, 54])



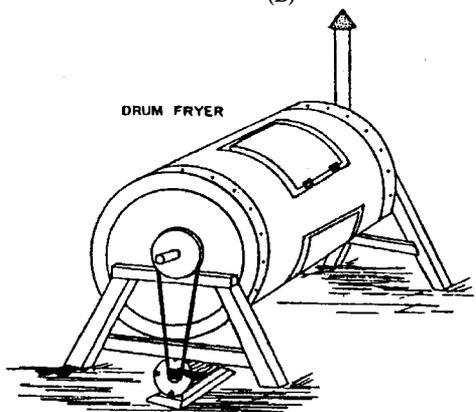
(A)



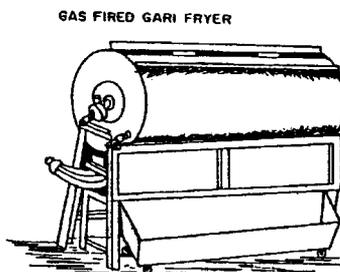
(B)



(C)



(D)



(E)

Figure 2.51. Equipment used for gari production. A, Hydraulic jack press; B, vibrating sieve; C, wood-fired gari fryer, D, drum fryer; E, gas-fired gari fryer. (Sources: [49, 54])

Table 2.29. Average nutritional composition of fresh cassava (wet-weight basis)

Component	Per 100-g Edible Portion
Food energy	146 cal
Water	62.5 g
Carbohydrate	34.7 g
Protein	1.2 g
Fat	0.3 g
Calcium	33 mg
Iron	0.7 mg
Vitamin A	Trace
Thiamine, B ₁	0.6 mg
Riboflavin, B ₂	0.03 mg
Niacin	0.6 mg
Vitamin C	36 mg

Source: [55].

Table 2.30. Some physicochemical properties of cassava roots relevant to its use as raw material for agroprocessing and value-adding

Property	Quantity
Dry matter	30%–40%
Starch	27%–36% FW
Total sugars	0.5%–2.5% FW
Protein	0.5%–2.0% FW
Fibre	1.0% FW
Lipids	0.5% FW
Vitamin A	17 g/100 g FW
Vitamin C	50 mg/100 g FW
Ash	0.5%–1.5% FW
Energy	607 kJ/100 g
Antinutritional factors	Cyanogens

Source: [3].

Table 2.31. Some thermophysical and rheological properties of cassava roots

Property	Quantity
Starch extraction rate	22%–25%
Starch grain size	5–50 μ m
Amylose	15%–29%
Maximum viscosity	700–1100 BU
Gelatinization temperature	49–73°C

Source: [3].

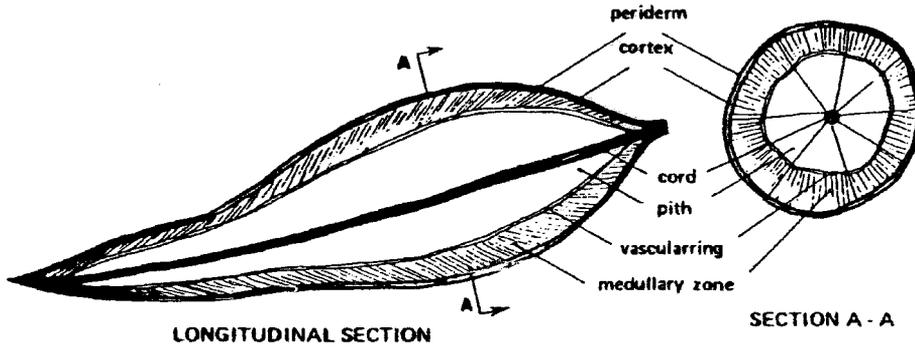


Figure 2.52. Sections through a cassava tuber. (Source: [56])

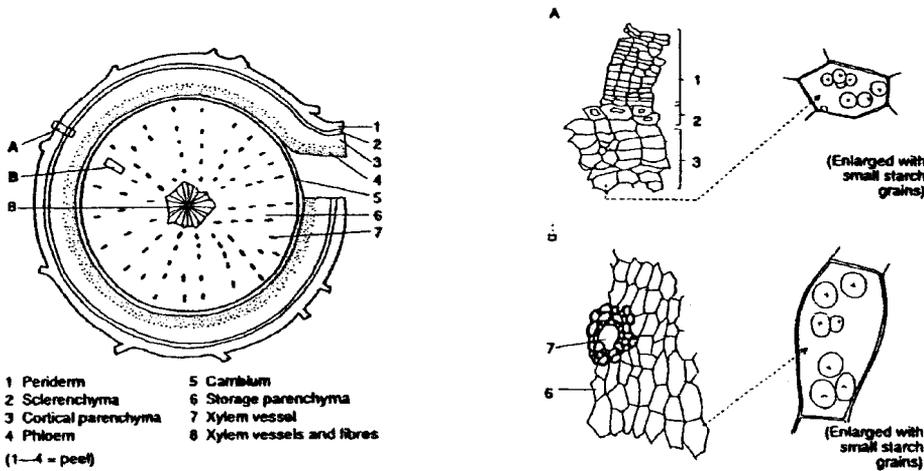


Figure 2.53. Transverse section showing relative size of starch grains in cassava root. (Source: [7])

Physical and Mechanical Properties

The physical and mechanical properties of agricultural and food materials are important parameters for designing handling and processing equipment. Typical cassava tuber geometry is shown in Fig. 2.54, with maximum tuber cross-sectional diameter occurring towards the stem region. Values of relevant physical properties are shown in Table 2.32. The coefficients of friction and rolling resistance (Table 2.33) between cassava tuber and various surfaces have been quantified. Mechanical properties relevant to the design of a cassava peeler also have been reported (Table 2.34). A range of other engineering properties of cassava tubers essential for design calculations for the mechanization of various agroprocessing operations or analysis of industrialization processes and systems also have been reported (Table 2.35).

Table 2.32. Physical properties of cassava tubers relevant to peeler design

Property	Minimum Value	Maximum Value	Average Value	Standard Deviation
Length (mm)	190	490	316.6	47.97
Weight (kg)	0.4	2	1.18	0.70
Diameter				
Big end (head)	34.8	82.9	60.40	10.38
Midway	19.6	65.1	46.60	9.76
Tail end	16.0	54.8	35.5	13.74
Peel thickness				
Big end (head)	1.1	2.8	1.9	0.40
Midway	1.0	2.3	1.6	0.36
Tail end	0.8	1.9	1.4	0.34

Source: [62].

Table 2.33. Average coefficients of friction and rolling resistance of cassava tubers on different surfaces

	Coefficient of Friction			Rolling Resistance Coefficient		
	Wood	Mild Steel	Aluminum	Wood	Mild Steel	Aluminum
Periderm	0.663	0.577	0.404	7.66	7.65	6.33
Cortex	0.577	0.532	0.344	7.41	7.29	6.42
Flesh	0.404	0.364	0.213	6.89	6.89	6.09

Source: [62].

Table 2.34. Some mechanical properties of cassava tubers

	Unpeeled Tuber	Peeled Tuber
Poisson's ratio	0.38	—
Shear stress ($\text{N}\cdot\text{mm}^{-2}$)	3.22	0.28
Peeling stress ($\text{N}\cdot\text{mm}^{-2}$)	0.30	—
Cutting force (N)	500	140
Rupture stress ($\text{N}\cdot\text{mm}^{-2}$)	0.95	0.70

Source: [62].

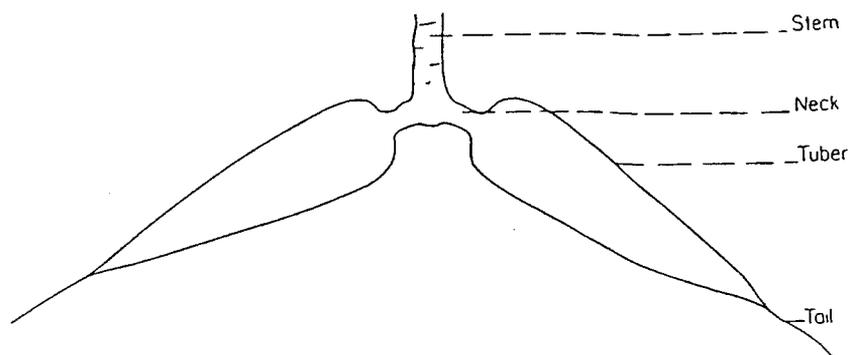
**Figure 2.54. Typical cassava tuber geometry. (Source: [61])**

Table 2.35. Some engineering properties of cassava roots and methods of determination

	Description (Mean Value)	Method of Determination
Shape	Spindle shaped; elongated ovoid; barrel shaped with rounded ends; conical with rounded ends (conical with rounded ends)	Comparison with known geometrical shapes
Roundness of transverse section	0.65 to 1.0 (0.85)	Actual area of section area of circumscribing circle
Length	10–55 cm (25 cm)	Direct measurement
Average straight length	10 cm	Direct measurement
Maximum diameter	2.5 to 15 cm (6.3 cm)	Direct measurement
Mass of individual tuber	25 to 4000 g (175 g)	Direct measurement
Mean specific gravity of whole root	1.025	Water displacement
Moisture content	Tail and midportion: 85% to 93% (w.b.) Head portion: 78% to 86% (88%) (w.b.)	Aerated oven
Solid density	1.92 to 2.3 g·cm ⁻³ (2.0 g·cm ⁻³)	Air comparison pycnometer using ground bone-dry tubers, average particle size 250 μ
Thickness of outer periderm	0.25 to 0.3 mm	Instron testing machine, time-displacement recording
Thickness of cortex	1.0 to 2.0 mm (1.5 mm)	Instron testing machine, time-displacement recording
Modulus of deformability or apparent modulus	3.45E+06–4.82 E+06 Pa	Tangent to stress–strain curve at designated stress
Bioyield strength	(9.3E+05 Pa)	Force–deformation curve in a compressive test
Shear strength	Medullary zone: 6.76E+05 Pa Central pith zone: 96E+05 Pa Section with chord: 2.14E+06 Pa	Double shear test using Instron testing machine
Specific heat	(0.94 J·kg ⁻¹ ·K ⁻¹)	Calorimeter method of mixtures
Thermal conductivity of tuber flesh	(0.285 W·m ⁻¹ ·K ⁻¹)	Modified Fitch Apparatus
Thermal conductivity of white gari at 610 kg·m ⁻³ bulk density	(0.61 W·m ⁻¹ ·K ⁻¹)	Thermal conductivity probe

Adapted from [56].

Note: Tests on unidentified variety of cassava from University of Florida Agricultural and Educational Center.

Effects of Processing on Biochemical Properties and Nutritional Properties

Processing of cassava roots affects the biochemical contents of the resulting products such as gari and flour. The two principal effects are the detoxification of the products and removal of moisture. In experiments with two bitter cassava cultivars, fermentation of the pulp for 96 hours during gari production reduced the hydrogen cyanide (HCN)

Table 2.36. Cyanide content of two bitter cassava cultivars and the effects of pH on cyanide level during processing

Time (h)	30572 Garri			30555 Garri		
	HCN Level \pm SD (ppm)	pH	Flour	HCN Level \pm SD (ppm)	pH	Flour
0	42 \pm 0.45	6.7	42 \pm 0.3	39 \pm 1.1	6.8	39 \pm 0.79
24	31 \pm 0.32	4.1	26 \pm 0.72	28 \pm 0.73	4.2	24 \pm 0.73
48	24 \pm 0.11	3.9	—	22 \pm 1.3	4.0	—
72	20 \pm 0.36	3.9	—	19 \pm 0.96	3.9	—
96	20 \pm 1.87	3.8	—	19 \pm 0.37	3.9	—
Product	12 \pm 0.81		20 \pm 0.11	10 \pm 0.37		19 \pm 0.87

Source: [60].

Table 2.37. Detoxification of cyanide during gari processing

Operation	Material	HCN (ppm)	Detoxification on peeled root (%)
Peeling	Whole cassava root	306	—
	Peel	660	—
	Peeled root	184	0
Grating	Slurry	104	16–92
Dewatering after fermentation	Cake	52	71.74
	Pressed juice	86	53.26
Roasting	Gari	10	94.56

Source: [55].

Table 2.38. Moisture content at various stages in gari processing

Operation	Product	Moisture content (%)
Grating	Slurry (pulp)	60–65
Fermentation	Fermented pulp	—
Dewatering (centrifuge)	Cake	47–50
Roasting	Semidry gari	30–35
Final drying	Gari	8–10

Source: [55].

content by 52% and 57% [60]. Soaking of the sliced tissue for 24 hours in cassava-flour production prior to sun-drying resulted in 38% reduction in HCN content for both cultivars. Gari processing reduced HCN content than cassava flour processing (Tables 2.36 and 2.37). In general, garification reduces moisture content to about 8% to 10% (Table 2.38). The low moisture content gives gari a good shelf life.

One of the very important quality attributes of gari is the swelling capacity in water, which should be at least three times the initial volume of the dry grits (Table 2.39). Particle size of gari ranges from below 50 μm (fine) to over 2000 μm (coarse). In practice, the quality of gari is judged by the degree of coarseness and moisture content

Table 2.39. Proximate composition of gari and fufu

Component	Village Gari	FIIR Gari	FIIR Fufu
Carbohydrate (% wt)	81.8	87.0	73.0
Water	14.4	8.2	8.6
Oil	0.1	0.1	0.44
Crude protein (N × 6.25)	0.9	1.5	1.26
Crude fiber (% wt)	1.4	2.3	1.60
Ash (% wt)	1.4	0.9	0.15
Calcium (mg/100 g)	17.7	45.6	—
Iron (mg/100 g)	2.0	2.2	0.001
Phosphorous (mg/100 g)	57.2	56.9	0.02
			5
HCN (ppm)	19.0	10.0	16.5
Swelling (% vol.)	320	300	—

Source: [63].

[17]. Free-flowing, granular meal and creamy-white color (or yellow if palm oil is added) are the attributes of good gari.

References

1. Cooke, R. D. 1978. An enzymatic assay for total cyanide content of cassava (*Manihot Esculenta*). *J. Sci. Food Agric.* 29:345–352.
2. CIAT. 1983. *Cassava Program Annual Reports for 1982 and 1983*. Cali, Colombia: International Center for Tropical Agriculture.
3. Wheatley, C., G. J. Scott, R. Best, and S. Wiersema. 1995. Adding value to root and tuber crops. A manual on product development. CIAT Publication No. 247, Bogota, Colombia.
4. Nweke, F. I. 1996. Cassava is a cash crop in Africa. *Tropical Root and Tuber Crops Bull.* 9(1):5–7.
5. Nweke, F. I., B. O. Ugwu, and A. G. O. Dixon. 1996. Spread and performance of improved cassava varieties in Nigeria. COSCA Working Paper No. 15, Collaborative Study of Cassava in Africa. Ibadan, Nigeria: IITA.
6. Dorosh, P. 1988. The economics of root and tuber crops in Africa. RCMP Research Monograph No.1, Resource and Crop Management Program. Ibadan, Nigeria: IITA.
7. IITA. 1990. *International Institute for Tropical Agriculture*. Ibadan, Nigeria: Author.
8. de Bruin, G. H. 1971. A study on the cyanogenetic character of cassava (*Manihot esculenta Crantz*). *Mededelingen Landbouwhogeschool Wageningen* No. 17–13:140.
9. Uritani, I., and E. D. Reyes, eds. 1984. *Topical Root Crops: Postharvest Physiology and Processing*. Tokyo: Japan Scientific Societies Press.
10. Coursey, D. G. 1982. *Traditional Tropical Root Crop Storage Technology: Some Interactions with Modern Science*. Sussex: Graphic Group.
11. Baybay, D. S. 1922. Storage of some root crops and other perishable farm products. *Philippine Agriculture* 10:429–430.

12. Coursey, D. G., and R. H. Booth. 1987. Postharvest problems of non-grain staples. *Acta Horticulturae* 53:23.
13. Passam, H. C., and R. A. Noon. 1977. Deterioration of yams and cassava during storage. *Ann. Appl. Biol.* 85:436.
14. Wheatley, C., and W. G. Janssen. 1985. Effects of the introduction of storage technology on the urban fresh cassava market of Colombia. In *Proc. 7th Symp. Int. Society of the Tropical Root Crops, Gosier (Guadeloupe)*, ed. L. Degras. Paris: INRA.
15. National Academy of Science. 1978. *Postharvest Losses in Developing Countries*. Washington, DC: U.S. National Academy of Science.
16. Odigboh, E. U. 1985. Mechanisation of cassava production and processing: A decade of design and development. University of Nigeria Inaugural Lecture Series No. 8. Nsukka: UNN.
17. Bencini, M. C. 1991. Post-harvest and processing technologies of African staple foods: A technical compendium. FAO Agricultural Service Bulletin 89. Rome: FAO.
18. Kader, A. A., ed. 1992. Postharvest technology of horticultural crops. University of California, Division of Agriculture and Natural Resources, Publication 3311. Davis: UC.
19. McGregor, B. M. 1987. Tropical products transport Handbook. U.S. Department of Agriculture, Agriculture Handbook No. 668.
20. Booth, R. H. 1977. Storage of fresh cassava (*Manihot esculenta*): II. Simple storage techniques. *Experimental Agriculture* 13:119–128.
21. Cock, J. H. 1985. *Cassava: A New Potential for a Neglected Crop*. Boulder, CO: Westview Press.
22. Kato, M. d. S. A., and S. M. C. Souza. 1987. Conservacao de raices apos a colheita. *Informe Agropecuario* 13(145):1–16.
23. Rickard, J. E., and D. G. Coursey. 1981. Cassava storage: 1. Storage of fresh cassava roots. *Tropical Science* 23:1–32.
24. Pantastico, Er. B., ed. 1975. *Postharvest Physiology, Handling and Utilisation of Tropical and Sub-tropical Fruits and Vegetables*. Westpoint, CT: AVI Publishing.
25. Snowdon, A. L. 1991. *A Colour Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables, vol. 2: Vegetable*. England: Wolf Scientific.
26. Tindall, H. D. 1983. *Vegetables in the Tropics*. London: MacMillan Press.
27. Hardenburg, R. E., A. E. Watada, and C. Y. Wang. 1986. The commercial storage of fruits, vegetables, and florist and nursery stocks. U.S. Department of Agriculture, Agriculture Handbook No. 66 (revised).
28. *Guide to Food Transport: Fruit and Vegetables*. 1989. Mercantilia Publishers.
29. SeaLand. 1991. *Shipping Guide to Perishables*. Iselin NJ: SeaLand Service Inc.
30. Burton, C. L. 1970. Diseases of tropical vegetables on the Chicago market. *Tropical Agriculture Trinidad* 47:144–152.
31. Ingram, J. S., and J. R. O. Humphries. 1972. Cassava storage: A review. *Tropical Sci.* 14:131–148.
32. Thompson, A. K. 1996. *Postharvest Technology of Fruit and Vegetables*. Oxford: Blackwell Science Ltd.

33. Singh, K. K., and P. B. Mathur. 1953. Studies in cold storage of tapioca root. *Bull. Central Food Tech. Res. Inst.* 2:181.
34. Cooke, R. D., J. E. Rickard, and A. K. Thompson. 1988. The storage of tropical root and tuber crops: Cassava, yam and edible aroids. *Experimental Agriculture* 24:457–470.
35. Thompson, A. K., and L. M. Arango. 1977. Storage and marketing cassava in plastic films. *Proc. Trop. Region Amer. Soc. Hort. Sci.* 21:30–33.
36. Young, N., T. S. deBuckle, H. Castel Blanco, D. Rocha, and G. Velez. 1971. *Conservacion de yuca fresca*. Bogota, Colombia: Instituto Investigacion Tecnologia.
37. Daniel, J.-F., B. Boher, and F. Kohler. 1981. Les maladies bacteriennes diu manioc (*Manihot Esculenta Crantz*) en Republique Populaire du Congo et en Republique Centrafricaine. *Agronomie* 1:751–757.
38. Oudit, D. D. 1976. Polyethylene bags keep cassava tubers fresh for several weeks at ambient temperature. *Journal of the Agricultural Society Trinidad and Tobago* 76:63–66.
39. Ryall, A. L., and W. J. Lipton. 1979. *Handling, Transportation and Storage of Fruits and Vegetables, vol. 1: Vegetables and Melons*, 2nd ed. Westport, CT: AVI Publishing.
40. Lozano, J. C., A. Bellotti, J. A. Reyes, R. Howeler, D. Leihner, and J. Doll. 1981. Field problems in cassava. CIAT Series No. 07EC-1, 2nd ed. Cali, Colombia: Centro Internacional de Agricultura Tropica.
41. Pacheco, J. A. de C. 1952. Alteracoes dequalidade da fecula durante a armazenamento das raizes de mandioca. *Bragantia* 12:297–298.
42. Booth, R. H. 1976. Storage of fresh cassava (*Manihot esculenta*): 1. Post-harvest deterioration and its control. *Expt. Agric.* 12:103–111.
43. Rickard, J. E. 1985. Physiological deterioration of cassava roots. *J. Sci. Food Agric.* 36:167–176.
44. Ekundayo, J. A., and T. M. Daniel. 1973. Cassava rot and its control. *Trans. British Mycol. Soc.* 61:27–32.
45. Marriott, J., B. O. Been, and C. Perkins. 1978. The aetiology of vascular discoloration in cassava roots after harvesting: Association with water loss from wounds. *Physiolgia Plantarum* 44:38–42.
46. Montaldo, A. 1978. Vascular streaking of cassava root tubers. *Tropical Sci.* 15:39–46.
47. Seaver, F. J., and J. M. Waterston. 1942. Contributions to the flora of Bermuda: 3. *Mycologia* 34:515–524.
48. Ponte, J. J. da, J. K. A. Mattos, M. A. da Ponte, F. M. Leite, E. V. Monte, and F. C. G. Almeida. 1977. Podridao seca das manivas: Comportamento de escacas de vez variedades de mandioca. *Fitopatologia Brasileira* 2:193–198.
49. Kwatia, J. T. 1986. Rural cassava processing and utilisation centers. UNICEF-IITA Collaborative Program for Household Food Security and Nutrition Report. Ibadan, Nigeria: IITA.
50. Ingram, J. S. 1972. Cassava processing: commercially available machinery. Tropical Products Institute Publication No. G75. London: Tropical Products Institute.

51. Roman, A. L. 1983. Naturally dried cassava chips: A solution to cassava marketing problems. *Cassava Newsletter* 7:5–7.
52. NSPRI. 1983. Storing your produce. Advisory Leaflet No. 3: Cassava and gari (revised). Nigerian Stored Products Research Institute. Oshodi, Nigeria.
53. Anazodo, U. G. N., C. O. Amadi, and B. O. Ikegbune. 1987. Indigenous technology development and commercialisation in Nigeria. FOPCIT Research and Development Report, vol. 1, no. 1. Enugu, Nigeria: Foundation for the Promotion and Commercialisation of Indigenous Technology.
54. Igbeka, J. C., M. Jory, and D. Griffon. 1992. Selective mechanisation of cassava processing. *Agricultural Mechanisation in Asia, Africa and Latin America* 23(1): 45–50.
55. Kwatia, J. T. 1986. Cassava: Storage, processing and utilisation. Paper presented at IITA-UNICEF Consultative Workshop on the Place of Cassava in the Household Food Security. Ibadan, Nigeria.
56. Odigboh, E. U. 1983. Cassava: Production, processing, and utilisation. In *HandBook of Tropical Foods*, ed. H. T. Chan, pp. 145–200. New York: Marcel Dekker.
57. Nartey, F. 1978. *Manihot Esculenta (Cassava): Cyanogenesis, Ultrastructure and Seed Germination*. Copenhagen: Munksgaard.
58. Coursey, D. G. 1973. Cassava as food. In *Cassava as Food: Toxicity and Technology*, pp. 27–36. Proc. Interdisciplinary Workshop, London (IDRC-OIOE).
59. Gondwe, A. T. D. 1974. Studies on the hydrocyanic contents of some local varieties of cassava and some traditional cassava food production. *East African Agric. Fores. J.* 40:161–167.
60. Kemdirim, O. C., O. A. Chukwu, and S. C. Achinenwhu. 1995. Effect of traditional processing of cassava on the cyanide content of gari and cassava flour. *Plant Foods for Human Nutrition* 48:335–339.
61. Onwueme, I. C., and W. B. Charles. 1994. Tropical root and tuber crops. Production, perspectives and future prospects. FAO Plant Production and Protection Paper No. 126. Rome: FAO.
62. Ohwovoriote, E. N., S. Oboli, and A. C. C. Mgbeke. 1988. Studies and preliminary design for a cassava tuber peeling machine. *Trans. ASAE* 31:380–385.
63. FAO. 1984. *Proceedings of the Workshop on Processing Technologies for Cassava and Other Tropical Tubers in Africa, Abidjan, Cote d'Ivoire, 28 Nov.–2 Dec., 1983*, vol. II. Rome: Author.

2.5 Yam Storage

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2.5.1 General

Terminology

The yam, also called *namé* (Spanish) and *igname* (French), belongs to the genus *Dioscorea* (family *Dioscoreaceae*). An estimated 300 to 600 species are available, but there are just over half a dozen principal species (Table 2.40). The most common species in the West African yam zone are *D. rotundata*, *D. alata*, and *D. esculenta*.

Table 2.40. Characteristics of important yam varieties and cultivars

	Common Names	Geographical Source	Characteristics
<i>D. rotundata</i> Cultivars: Guinea blanco, Guinea negro, Akandou, Lokpa, Kangba, Krengle	White yam, white guinea yam	West Africa, West Indies, and Caribbean	Compact spherical or cylindrical tubers; white, cream, and yellow fleshed with large, ovoid starch grains; circular stem may be smooth or spiny and twists to the right when climbing; opposite leaves
<i>D. alata</i> Cultivars: White Lisbon, Florido, Forastero, Nza seguela, Oriental, Bete bete	Water yam, greater yam	Southeast Asia and Caribbean	Cylindrical, white purplish with loose watery texture; winged stem twists to the right in climbing; opposite leaves
<i>D. cayensis</i>	Yellow yam, guineas yam	West Africa and West Indies	Yellow-fleshed, firm-skinned, very similar to <i>D. rotundata</i> ; drought-intolerant
<i>D. esculenta</i> Cultivars: De papa, De pana, Chinese	Asiatic yam, lesser yam, potato yam	China, Southeast Asia, South Pacific, Caribbean	Forms numerous excellent-flavored tubers with smooth thin yellow-brown skin, and white, sweet-fleshed grained starch; thorny stems twine to the left with alternate leaves
<i>D. dumetorum</i>	Bitter yam, trifoliolate yam	West Africa	Bitter-fleshed; some are poisonous
<i>D. bulbifera</i>	Aerial yam, potato yam	West Indies, Africa, and Asia	Forms bulbils, glabrous vine twists to the right; leaves alternate; low palatability; some clones have acrid tastes or contain alkaloids
<i>D. trifida</i>	Yampie, cush-cush yam	West Indies	Yams range from white, yellow, and pink to purple with good flavor; low yield.
<i>D. opposita</i>	Cinnamon yam, Chinese yam	China, Korea and Japan	Cold-tolerant, used in medicinal purposes
<i>D. japonica</i>		Japan and China	Cold-tolerant
<i>D. pentaphyla</i> Cultivar: Wahnad		Indonesia and Pacific	Yams borne in cluster; can be grown for several years prior to harvest
<i>D. nummularia</i> Cultivar: Wail		Indonesia and Pacific	

Sources: [1–3].

Table 2.41. World production of yam (*Dioscorea*) in 1975

	Area (10 ³ ha)	% of World Area	Production (10 ³ ton)	% of World Production	Yield (ton·ha ⁻¹)	% of World Yield
World	2110	—	20,198	—	9.6	—
Africa	2049	97.1	19,539	96.7	9.4	97.9
North and Central America	22	1.0	243	1.2	11.1	115.6
South America	10	0.5	48	0.2	4.7	0.5
Asia	15	0.7	168	0.8	11.4	118.8
Oceania	15	0.7	200	1.0	13.5	140.6
Leading countries						
1. Nigeria	1350	64.0	15,000	74.3	11.1	115.6
2. Cote d'Ivoire	200	9.5	1700	8.4	8.5	88.5
3. Ghana	160	7.6	800	4.0	5.0	52.1
4. Togo	100	4.7	750	3.7	7.5	78.1
5. Benin	59	2.8	610	3.0	10.3	107.3

Adapted from [4].

Table 2.42. Production of world's leading yam producers in 1990

	Area (10 ³ ha)	% of World Area	Production (10 ³ ton)	% of World Production	Yield (ton·ha ⁻¹)	% of World Yield
World	2928	100	29,447	100	10.06	100
Africa	2789	95.3	28,249	95.6	10.13	100.7
West Indies	59	2.0	350	1.2	6.12	60.9
Oceania	18	0.6	284	1.0	15.82	157.3
Asia	15	0.5	198	0.6	12.88	128.0
Nigeria	1900	64.9	22,000	74.7	11.58	115.1
Cote d'Ivoire	266	9.1	2528	8.6	9.50	94.5
Benin	90	3.1	992	3.4	11.03	109.6
Ghana	200	6.8	168	2.4	3.50	34.8
Togo	40	1.4	420	1.4	10.50	104.4
Zaire	38	1.3	270	0.9	7.20	71.6

Adapted from [5].

Economic Importance

Yams are considered second to cassava as the most important tropical root crop. The yam is an important crop in many parts of the tropical and subtropical regions, where it is a major part of the diet. Most of the world production is from Africa (about 96%), with Nigeria alone accounting for nearly 75% of the total world production (Tables 2.41 and 2.42). World annual production was estimated to be 25 million ton in 1974 [1], and 24 million ton in 1992 [6]. Further information on yam production statistics (1979-89) can be found in ref. [7].

In the South Pacific, the yam is a significant food crop, accounting for over 20%, 8.1%, and 4.6% of the total dietary calorie intake in the Kingdom of Tonga, Solomon Islands, and Papua New Guinea, respectively. In addition to its importance as food

Table 2.43. Annual percentage growth of the per capita production of yams in Africa

	1964–74	1974–84
West Africa	–0.3	–1.1
Central Africa	–1.2	–1.8

Source: [8].

source, the yam also plays a significant role in the sociocultural lives of some producing regions, for example through the famous yam festivals in West Africa. In some parts of southeastern Nigeria, boiled and mashed yam is often the principal meal offered to gods and ancestors. Until recently, newly married couples in the yam zone of West Africa were presented with good-quality yam tubers for planting to assist them in raising a family. Due to its relatively longer storage life compared with other fresh produce in the tropical developing countries, stored yam represents stored wealth that can be sold year-round to derive income.

During the period from 1975 through 1990, the world's area cultivated with yams increased by about 38.8% and total production increased by 45.8%, presumably due to improved cultivation practices in most areas. However, the importance of yam in the economy of the main producing areas appears to be declining due partly to competition with other crops, such as cassava in Nigeria and taro in the South Pacific. The major producing areas also have continued to experience high population growth rates. For instance, the annual growth rate of per capita production in the major yam zones in Africa has declined during the past four decades (Table 2.43).

Postharvest Losses

Losses occur at various stages from production, postharvest handling, marketing, and distribution. This includes losses in quantity and tuber quality, arising from physical damage and biotic (fungi and bacteria), and physiological (sprouting, dehydration, respiration) factors. Estimated loss of total crop is in the range from 10% to 60% [9]. Losses in tuber weight occurring during storage in traditional or improved barns or clamp storage can reach about 10% to 12% in the first 3 months and 30% to 60% after 6 months. Weight losses of 33% to 67% after 6 months storage have been reported [10]. In West Africa alone, this was equivalent to an annual loss of 1 million ton of tuber [11]. The magnitude of weight loss in stored yams increases rapidly after the first months (Table 2.44). Transit losses of about 15% to 40% occur in some developing countries where there is a lack of storage or poor storage and transport facilities for tubers. Losses of *D. alata* cultivars have varied from 7% to 23% during 4 months of storage [12], and in Puerto Rico, postharvest losses of yams due to decay have exceeded 50% [13]. High postharvest losses of yams during any season often translates into higher market prices due to the reduction in the amount of available crop.

Several factors contribute to storage losses in yams, with the most important the autolytic processes and attack by fungal or bacterial biodeteriogens. Physical processes include mechanical damage such as crushing or breakage and spillage or loss as from

Table 2.44. Weight losses in stored yams

Country	Species	Weight Loss During Storage (%)				
		1 mo	2 mo	3 mo	4 mo	5 mo
Puerto Rico	Guinea yams	1	3	8	(sound tubers)	
		2	6	11	(tubers slightly infected by rots)	
Nigeria	<i>D. rotundata</i>	5	7	12	20	29
		4	6	10	14	21
		3	6	14	23	30
	<i>D. cayenensis</i>	6	17	29	39	48
Ghana	<i>D. rotundata</i>	1	5–7	15–17	26–27	34–40

Source: [10].

faulty container. Autolytic processes give rise to chemical or biochemical changes in the tuber as a result of interaction amongs parts of the tuber or between it and the atmosphere or the environment. Infestation by insects or other arthropods can destroy all or part of the produce and cause the partial or complete spoilage of any that remains. Microbiological attack by biodeteriogens such as fungi and bacteria has deleterious effects on stored produce, especially in warm tropical climates. Finally, rodents and higher animals feed on and also can damage the produce.

2.5.2 Maturity and Harvesting

Maturity

Yams follow four distinct growth periods: sprouting, root growth, tuber enlargement, and maturation [2, 14, 15]. Mature crop often is characterized by cessation of vegetative growth and yellowing of leaves. The period from planting or field emergence to maturity is variable depending on the species (Table 2.45). There is currently no reliable and objective index of yam-tuber maturity, although some crude indices have been reported

Table 2.45. Characteristics of yam species

Species (Common Name)	Period from Planting to Maturity	Yield and Size of Tubers
<i>D. alata</i> (water yam)	220–300 d	20–25 ton·ha ⁻¹ ; 1–3 tubers per plant; 5–10 kg per tuber
<i>D. bulbifera</i> (potato yam)	140–180 d; 90–120 d	Aerial: 2–15 ton·ha ⁻¹ ; 3–5 ton·ha ⁻¹ ; underground: 2–8 ton·ha ⁻¹
<i>D. cayenensis</i> (yellow yam)	280–350 d	30 ton·ha ⁻¹ ; 2 kg per tuber (mean); 7–10 kg per tuber (maximum)
<i>D. dumentorum</i> (bitter yam)	240–300 d	Greater than those of most other cultivated West Africa yams
<i>D. esculenta</i> (lesser yam)	200–300 d	7–20 ton·ha ⁻¹ ; 25–35 ton·ha ⁻¹ (exceptional); 5–20 tubers per plant
<i>D. opposita</i> (Chinese yam)	24 wk	4–6 ton·ha ⁻¹
<i>D. rotundata</i> (white yam)	200–330 d	16–20 ton·ha ⁻¹
<i>D. trifida</i> (cush-cush yam)	280–330 d	15–20 ton·ha ⁻¹

based on the percentage of tuber length that is whitish at harvest, nonfriable after cooking, or bitter after cooking [16]. The most frequently reported measure is the period from planting to harvest (growing period), but it has been suggested that the time from emergence to maturity provides a better measure of growing period, because planted tuber can remain dormant for some time [17].

Most edible yams reach maturity 8 to 11 months after planting. Techniques such as using physiologically aged planting material, presprouting of setts [16], application of sprout-promoting substances (e.g., ethephon and 2-chloroethanol) [18, 19], and harvesting before complete shoot senescence can decrease the duration of field dormancy and thereby reduce the length period from emergence to maturity. Common pests are beetles and rodents, and these can reduce yields and tuber quality significantly. In general, yams are very resistant to fungi, but some cultivars such as *D. alata* are more susceptible. In many parts of the West African yam zone, mature yams are harvested at the end of the rainy season or in the early part of the dry season, which coincides with the end of vegetative growth.

Harvesting

Harvesting is by traditional methods of digging, which are labor-intensive. Sticks and spades made of wood are preferred to metallic tools, as they are less likely to damage the fragile tubers. Harvesting of aerial tubers or bulbs is usually by manual plucking from the vine. Although some success in mechanical yam harvesting has been reported, especially for *D. composita* tubers for pharmaceutical uses [20], various noncommercial equipment is available. The use of a potato spinner has been suggested for harvesting species that produce a number of small tubers [17]. Successful mechanization of yam harvesting would require extensive changes in current traditional cultivation practices, including staking and mixed cropping, and possibly in tuber architecture and physical properties.

Yams can be harvested once (*single-harvesting*) or twice (*double-harvesting*) during the season to obtain a first (early) and second (late) harvest. The first harvest has also been referred to by the terms “topping,” “beheading,” and “milking,” all of which have been considered inadequate and obsolete [16]. In single-harvesting, each plant is harvested once; this occurs at the end of the season when crop is mature. The harvesting process involves digging around the tuber to loosen it from the soil, lifting it, and cutting from the vine with the corm attached to the tuber. The time of harvest is critical in terms of tuber maturity, yield, and postharvest quality. Depending on the cultivar, the period from planting or emergence to maturity varies from about 6 to 7 months [17] or even 6 to 10 months.

For double-harvesting, periods of 8 to 10 months and 4 to 5 months from planting or emergence to maturity have been recommended [1, 17]. First harvest at 5 to 6 months after planting and the second 3 to 4 months later also have been reported [3]. The first harvest is made by removing the soil around the tuber carefully and cutting the lower portion, leaving the upper part of the tuber or the “head” to heal and continue to grow. The soil is returned and the plant is left to grow until the end of the season for the second harvest. Some yam cultivars produce several small tubers in the second growth following

the early harvest. Double-harvesting is most applicable to short-term varieties such as *D. rotundata*, and to *D. cayenensis* and *D. alata* to lesser extents.

A comparison of single- and double-harvesting showed that yields were similar and plants senesce at about the same time. However, single-harvested tubers had better eating quality than the double-harvested tubers. More detailed comparison can be found in ref. [17].

Tuber Yield

The average yield of tubers is variable among the major producing areas (see Tables 2.41 and 2.42). Yield also depends on the species (see Table 2.43), seed piece, and growing environment; it ranges from 8 to 50 ton·ha⁻¹ in 6 to 10 months. Yields of 8 to 30 ton·ha⁻¹ in commercial yam production also have been reported, the exact value depending on the location, variety, and cultivation practices [17]. In Nigeria, yam tuber yields varied with ecology, ranging from 10 ton·ha⁻¹ in Onitsha (forest zone) and Abakaliki (derived savanna) to 40 ton·ha⁻¹ in Zaki-Biam (Guinea savanna) from planting densities of 2500, 2700, and 12,000 stands per hectare, respectively [11]. Many yam cultivars produce only a single large tuber, and the approximate multiplication ratio (fresh-weight yield to weight of planting material) for the yam is 5. Between 1975 and 1990, there were yield increases in all major producing countries except Ghana. During this period, the average world yield increased by nearly 11%.

2.5.3 Postharvest Handling, Curing, and Packaging

Yams are fragile and susceptible to physical damage during harvesting and postharvest handling. Injury can lead to infection by rotting organisms and loss during subsequent storage. Injury also accelerates the respiration rate of tubers, which may lead to rapid weight loss and development of shrivel. Physical damage of yam tubers can be classified as follows [21]:

Digger cuts: the digger point cutting the tuber in two parts

Break-off injuries: the breaking off of rounded protuberances at the tail (distal) end or on the surface of the tubers

Serious bruises: bruises that cause the skin to peel off over more than 20% of the tuber surface; may be caused by the tubers being stepped on during harvesting

Small bruises: surface thumbnail cracks, less than 1.2 cm long, that do not remove the flesh of the tuber

Packaging tubers in full-telescopic fiberboard cartons with paper wrapping or excelsior reduces bruising during postharvest handling. Tubers can be contained in loose packs, or units of 11 kg and 23 kg [22]. For transportation, the cartons are hand-loaded or unitized on pallets.

Curing allows suberization of surface injuries and reduces weight loss and rotting in root crops. Postharvest curing of yams is recommended before storage of tubers so as to “heal” any physical injury that may have occurred during harvesting and handling. Curing can be accomplished under tropical ambient conditions or in a controlled environment. Traditionally, yams are cured by drying the tubers in the sun for a few days. The optimum

Table 2.46. Effects of packaging material on the quality of *D. trifida* after 64 days at 20–29°C and 46%–62% relative humidity

Type of Package	Weight Loss (%)	Fungal Score ^a	Necrotic Tissue ^b (%)
Paper bags	23.6	0.2	5
Polyethylene bags with 0.15% of the area as holes	15.7	0.2	7
Sealed 0.03 mm-thick polyethylene bags	5.4	0.4	4

Source: [23].

^a Fungal score: 0 = no surface fungal growth, 5 = tubers surface entirely covered with fungi.

^b Estimated on the total cut surface of lengthwise halves.

conditions for curing are 29 to 32°C at 90% to 96% relative humidity for 4 to 8 days [22]. Tubers cured at higher temperature (40°C) for 24 hours or treated with gamma radiation at 12.5 krad were free of mold and had the least loss during subsequent storage. Storing at 15°C with prompt removal of sprouts improves the eating quality of tubers [11].

Modified atmosphere packaging has beneficial effects in yam storage, especially if appropriate packaging material and quantity, size, and number of holes are utilized. Sealing yam tubers in polyethylene-film bags reduced storage losses due to weight loss and development of necrotic tissue (Table 2.46). Coating tubers with a commercial vegetable wax (Epolene E10) improved the appearance quality, but there was no effect on levels of fungal infection [23]. The effect on tuber weight loss was inconsistent.

2.5.4 Storage-Environment Requirements

Under favorable environments, yams can be stored for several months and some cultivars for longer, but loss in flavor and quality occurs in storage. Precooling can be achieved at room conditions. The three main requirements for yam storage are aeration, reduction of temperature, and regular inspection of produce. Aeration prevents moisture condensation on the tuber surface and assists in removing the heat of respiration. Low temperature is necessary to reduce losses from respiration, sprouting, and rotting; however, cold storage must be maintained around 12 to 15°C, below which physiological deterioration such as chilling injury occurs. Regular inspection of tubers is important to remove sprouts and rotted tubers, and to monitor the presence of rodents and other pests. In general, tubers should be protected from high temperatures and provided with good ventilation during storage. The storage environment also must inhibit the onset of sprouting (breakage of dormancy), which increases the rate of loss of dry matter and subsequent shrivel and rotting of tuber.

Fresh Tuber Storage

Fresh yam tubers can be stored successfully in ambient and refrigerated conditions, but there are differences among cultivars (Table 2.47). The recommended storage temperature is in the range from 12 to 16°C. Optimum conditions of 15 or 16°C at 70% to 80% [22] or 70% relative humidity [1] have been recommended for cured tubers. Transit

Table 2.47. Recommended storage conditions for yams (*Dioscorea* spp.)

Cultivar or Common Name	Temperature (°C)	Relative Humidity (%)	Length of Storage
<i>D. trifida</i>	3	—	1 month
<i>D. alata</i>	12.5	—	8 weeks
<i>D. alata</i>			
Cured	15–17	70	180 days ^a
Noncured	15–17	70	150 days ^b
<i>D. cayenensis</i>	13	95	<4 months ^c
Water yam, greater yam	30	60	several months ^d
Elephant yam	10	—	several months
White yam, Guinea yam	16	80	several months
Yellow yam, 12-month yam	16	80	60 days
Cush-cush, Indian yam	16–18	60–65	several months ^e
Lesser yam, Chinese yam	25	—	60 days ^f
Cultivar Unknown	13.3	85–90	50–115 days
	16	65	4 months
	16	70–80	6–7 months

Adapted from [24–31].

^a Weight loss, 11%.

^b Weight loss, 12%–25%.

^c About 29% weight loss, and internal necrosis occurred.

^d Ventilated storage in barns.

^e Barn storage.

^f Ventilated storage.

and storage life of 6 to 7 months can be achieved under these conditions. Ware yam and seed yam have similar storage requirements. The onset of sprouting is enhanced at ambient conditions, especially if ventilation is inadequate. For example, during storage at ambient conditions (20–29°C, 46%–62% relative humidity), *D. trifida* began to sprout within 3 weeks [32]. There is very limited information on the storage conditions for *D. opposita*, but it was reported that it can be stored over winter in clamps or cold stores in Japan [24].

Yam-tuber decay occurs at higher humidity, and like most tropical crops it is susceptible to chilling injury at low storage temperatures. To avoid tuber damage, minimum storage temperatures of 10, 12, and 13°C [1, 22], at or below which chilling injury occurs, therefore have been recommended. Storage of *D. rotundata* tubers at 12.5°C resulted in chilling injury [33], and storage of *D. alata* at either 3 or 12°C resulted in total physiological breakdown within 3 to 4 weeks [34]. Storage of *D. alata* at 5°C for 6 weeks gave good results, but chilling injury symptoms developed rapidly when tubers subsequently were put in ambient (25°C) conditions [26].

Yams are also sensitive to ethylene. On a scale of high, medium, and low moisture-loss rates, yams suffer medium loss rates compared with other fruits and vegetables [35]. The economics of using improved cold-storage technology (about 15°C) and other postharvest technologies (such as gamma radiation with 7.5–15 krad) in yam storage are not clear and these must be evaluated before these technologies are introduced for use in specific local situations.

Controlled-Atmosphere Storage

No significant beneficial effects of controlled atmospheres on commercial yam storage has been demonstrated. In general, controlled-atmosphere storage has minimal effect on yam storage [28]; however, fully mature *D. opposita* tubers can be stored for long periods of time at high O₂ tensions or at 5°C. These conditions reduced the incidence of tuber browning [36].

Storage of Processed Yam Products

Processed yam products such as dried chips, biscuits, and flour generally are not stored for long periods. A variety of packages is used for storage including baskets, gunny bags, polyethylene bags, polyethylene-lined jute bags, and basins made of plastic or metal. Packaging can occur before or after storage in room conditions or in silos. It is important to exclude moisture, insects (mostly *Araecerus fasciculatus* De G. and *Sitophilus zeamays* Mots), and rodents. If the same packaging is used for other products, fumigation with phostoxin by placing the tablets on or in the bags and covering with a gas-proof sheet is recommended.

2.5.5 Tuber Dormancy in Storage

Dormancy is the temporary suspension of visible growth of any plant structure containing a meristem [37]. In stored yam tubers, this refers to the period during which sprouting is inhibited. The end of dormancy thus is marked by the onset of sprouting. Knowledge of the potential length of dormancy for stored tuber is important because once dormancy breaks, the tubers also senesce rapidly, with loss of the stored food carbohydrate [38]. Yam tuber does not sprout during the early part of storage, even under suitable growth conditions. The environmental conditions affecting yam-tuber dormancy are photoperiod, white and colored lights, temperature, relative humidity, and partial oxygen pressure [39].

The length of tuber dormancy is endogenously controlled, and conditions such as availability of soil moisture [40] or cool temperature [10] are ineffective triggers of sprouting. Physiological age of tubers affects their readiness to sprout, but by approximately 6 months after harvesting, dormancy disappears completely and budless setts planted after that period will require nearly the same time to sprout [41]. The length of the dormant period depends on the yam species (Table 2.48).

2.5.6 Storage Disorders and Diseases

Sprouting

Sprouting marks the breakage of dormancy in yams. Sprouts are initiated in a meristematic region about 1 cm from the edge of the tuber. Different stages occur during the internal formation of the sprout (Fig. 2.55) and the external development (Fig. 2.56) [2, 16, 17]. During storage, one or more buds may develop from the head region of yam tuber. Although the mechanism in the yam tuber is not clear, dormancy has been associated with low levels of glutathione in the tuber [40], and batatasins may play a role

Table 2.48. Length of dormancy of tubers of major edible yam species

	Locality	Period of Dormancy (wk)
<i>D. alata</i>	Caribbean	14–16
	Nigeria	14–16
<i>D. bulbifera</i>	Nigeria	19–20
<i>D. cayenensis</i>	Nigeria	4–8
<i>D. dumetorum</i>	Nigeria	14–16
<i>D. esculenta</i>	Caribbean	4–8
	Nigeria	12–18
<i>D. rotundata</i>	Nigeria	12–14
		14–16
<i>D. trifida</i>	Caribbean	2–4

Adapted from [26, 40, 42–44].

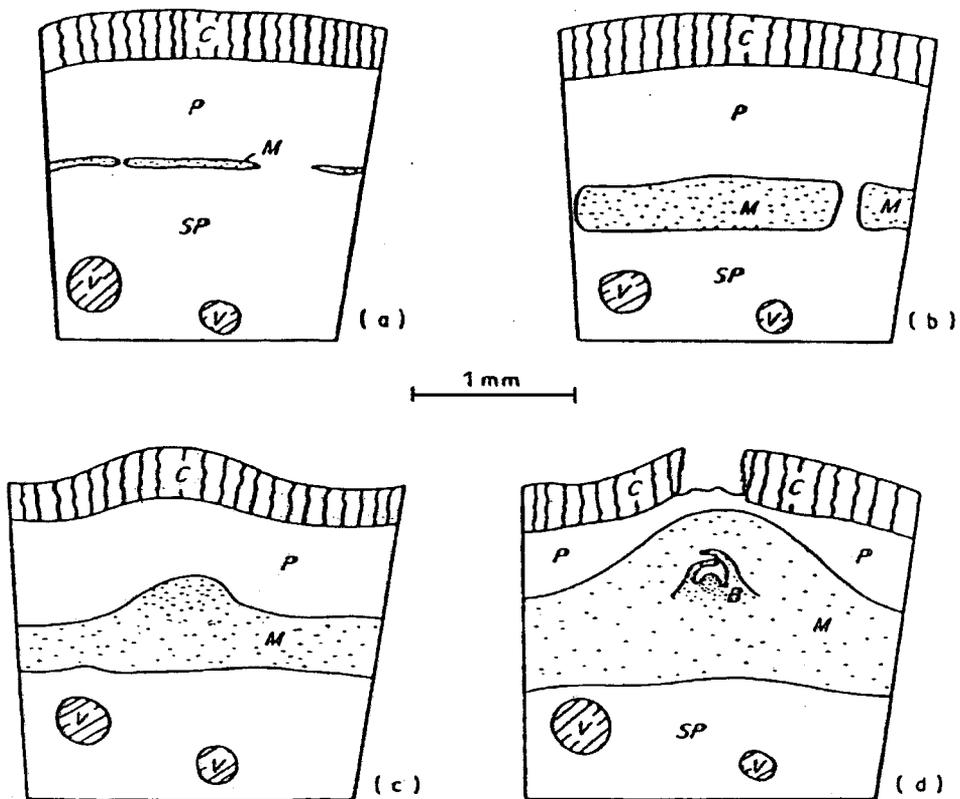


Figure 2.55. Progressive stages in sprout formation in *D. rotundata*. C, Cork layer; M, layer of meristematic cells; P, parenchyma cells with only small amount of stored starch; SP, storage parenchyma with stored starch and constituting the bulk of the tuber; V, vascular bundles.

(Source: [45])

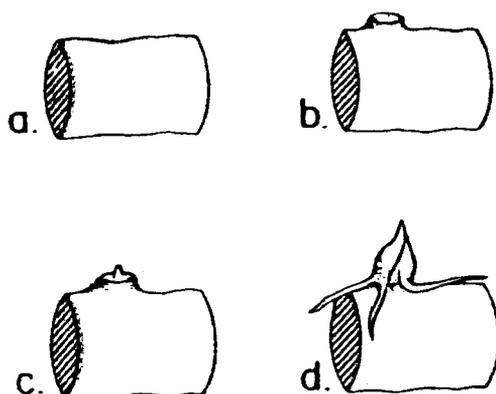


Figure 2.56. Stages in the sprouting of *Dioscorea* tuber. a, Normal tuber piece before planting; b, formation of sprouting locus; c, appearance of differentiated shoot buds; d, enlargement of the shoot bud and development of roots. (Source: [45])

[46]. However, sprouting is dependent on the time of harvest and storage temperature. Tubers sprout rapidly at ambient temperatures (25–30°C) and high relative humidity once dormancy is broken. Sprouting is a major source of dry-matter loss. Rootlet formation requires high humidity to occur. Sprouting can be a problem in storage, but the sprouts can be rubbed off during inspection of tubers. Sprout formation is considerably delayed at 35 or 15°C. Thus, leaving unharvested or planted tubers in the soil may expose them to supraoptimal temperatures, which may inhibit sprouting or retard their sprouting in many tropical areas in which soil temperatures exceed 35°C for several hours nearly every day [17].

Irradiation of yam tubers with gamma rays has been used successfully in yam storage to control sprouting. The optimal dose for sprout inhibition varies with yam species, but 7.5 krad appears to be the critical dose [47]. The higher the dose, the lower the percentage of rotting up to 15.0 krad, beyond which the percentage of rotting increases. In a trial with eight cultivars of *D. rotundata*, irradiation between 5 and 20 krad caused 50% reduction in weight loss in comparison with controls [48, 49]. To achieve complete suppression of the nematode population in infected yam tubers, a dose of 30 krad was required [50]. It has been postulated that the inhibition of sprouting in irradiated yams is due to interference with nucleic acid metabolism in the meristem tissue [39].

Control of Diseases and Pests

Yams are susceptible to preharvest attack by the yam beetle and microorganisms such as nematodes and yam virus. The major postharvest disease is tuber rot, caused mostly by fungi. The types of diseases and pests and their control measures are summarized in Table 2.49. Fumigation is with methyl bromide, but practitioners should note that the use of such chemicals in agriculture and food processes is now prohibited or strictly regulated in many countries and regions. Rodents can be controlled by fencing, poisoning, and

Table 2.49. Pests and diseases in yams

Common Name	Organism	Incidence and Characteristics	Control Strategy
Yam beetle	<i>Heteroligus meles</i>	A major pest in West Africa; adults migrate by flying to other farms/plots; they feed on the tuber, thereby leaving holes on them; tubers loss appearance quality and become prone to rotting during storage	Dusting of the sets with insecticide before planting (note that some insecticides can be persistent and harmful to the environment); very late planting can reduce infestation but affect yields
Chrysomelid beetle	<i>Lilioceris livida</i>		Removal of larvae by hand or spraying carbaryl
Scales	<i>Aspidiella hartii</i>		Removal of pests with a brush and treatment with diazinon plus white oil or malathion prior to planting
Mealy bugs	<i>Planococcus citri</i>		Use of clean stock
Yam anthracnose	Fungi such as <i>Colletotrichum</i> and <i>Glomerella ingulata</i> implicated.	Occurs in all yam-producing areas; infection from inoculum borne within the planting set or in; the soil results in blackening and die-back of the leaves and shoot	Use of resistant cultivar (e.g., TDA 291, TDA 297), maneb or benomyl, and good field sanitation
Nematodes	Yam nematode (<i>Scutellonema bradys</i>) and the root knot nematode (<i>Meloidogyne</i> spp.) are the most serious	They reside in the tuber and remain active during storage; wounded areas provide entry for decay-causing bacterial and fungi	Crop rotation and fallowing, and planting with healthy materials; soil fumigation with nematicides may be uneconomical
Yam virus complex		Occurs throughout the West African yam zone; reduces yields considerably	Use of virus-free planting materials or resistant cultivars; thermotherapy and meristem culture
Tuber rots	Soft rots caused by <i>Penicillium</i> spp., <i>Fusarium oxysporum</i> , and <i>Botrydiplozia theobromae</i> ; dry rots caused by <i>Rosselinia</i> and <i>Sphaerostilbe</i>	Infection in the field can lead persist and to rotting during storage	Planting with disease-free material; crop rotation; minimizing of physical damage to tuber during postharvest operations; treating of the set or tuber with systemic fungicide or alkaline material such as Bordeaux mixture; adequate aeration and regular inspection of stored tuber

Adapted from [1, 17, 51].



Figure 2.57. Traditional “yam house.”

trap setting. There are extensive reviews in the literature on yam pests and diseases and their control measures [10, 17, 25, 39].

2.5.7 Types of Storage Structures

Traditional Shelters

Leaving the tubers in the ground until harvest is required is the simplest storage technique practiced by some rural farmers. This underground, on-farm storage, however, prevents the use of the farmland for further cropping. In some parts of West Africa and Oceania, individual tubers are suspended from a horizontal pole supported about 1 to 2 m above the ground by two forked sticks. Harvested yams also can be put in ashes and covered with soil, with or without grass mulch as shelter. “Yam houses” frequently are found in many yam-growing regions. These have thatched roofs and wooden floors, and the walls sometimes are made simply out of bamboo (Fig. 2.57).

The yam barn is the principal traditional yam storage structure in the major producing areas. Barns usually are located in shaded areas and constructed so as to facilitate adequate ventilation while protecting tubers from flooding and insect attack. There are several designs, but they all consist of a vertical wooden framework to which the tubers are individually attached. Most barns are constructed in a shaded enclosure to protect tubers from direct sunlight (Fig. 2.58). In a typical yam barn, galvanized iron was used to protect the structure against rats which were considered a major problem during tuber storage (Fig. 2.59).

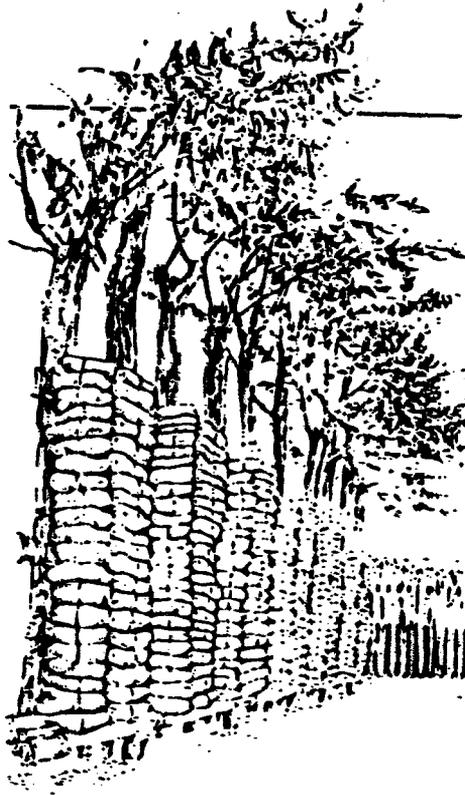


Figure 2.58. Inside view of a yam barn.
(Source: [52])

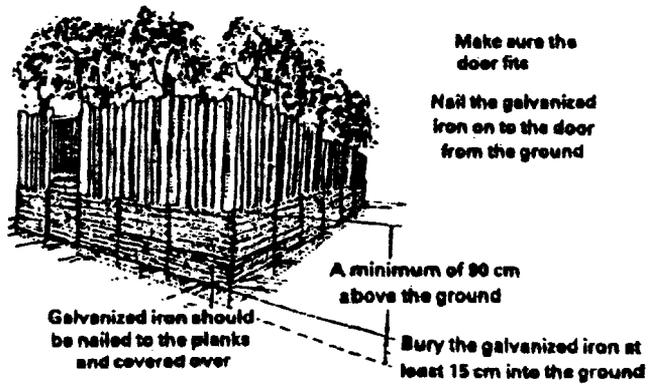


Figure 2.59. Protection of a shaded yam barn against rats.
(Source: [52])

Two tubers are tied to a rope at each end hung on horizontal poles 1 to 2 m high. Barns up to 4 m high are also not uncommon. Depending on the quantity of tuber to be stored, frames can be 2 m or more in length. The ropes are usually fibrous, but in southeastern Nigeria they are made from the raffia obtained from top part of the palm wine tree. Many farmers have permanent barns that need annual maintenance during the year's harvest. In these situations, the verticals posts often are made from growing trees, which are trimmed periodically. Palm fronds and other materials are used to provide shade. The vegetative growth on the vertical trees also shades the tubers from excessive solar heat and rain. The use of open-sided shelves made from live poles, bamboo poles, or sawn wood has been recommended to enable careful handling and easy inspection in comparison with tying tubers to poles, which can cause physical damage and rotting [7]. In barn storage, yams have a maximum storage life of 6 months, and therefore barn storage is most suited for long-term varieties. Storage losses can be high (10%–15% in 3 months, and 30%–50% after 6 months) if tubers are not treated for rotting using fungicides such as Benlate, Captan, or Thiabendazole.

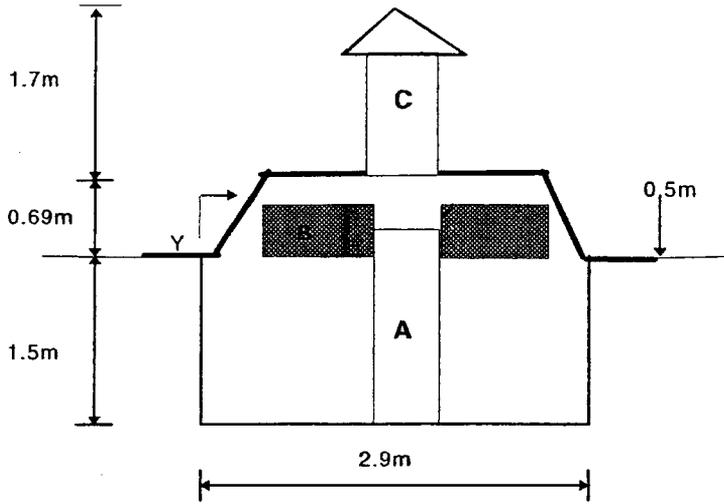
Another traditional storage involves stacking yams in small heaps in crevices of rock outcrops or large trees near the house or in the farm. Similarly, they can be heaped in loose bulk on the floor. Yams also are stored in raised platforms or on shelves in sheds or huts used for other purposes, such as maize cribs, or specially constructed for yam storage. Such stores usually are located in the shade of large trees, and the yams are stacked up to the top. This type of structure entails considerable handling of the tubers and therefore is suited for the varieties more resistant to physical injury. In some regions such as the South Pacific, such raised platforms contain only one or two layers of yams to ensure that adequate aeration is provided and that inspection can be carried out easily. Leaves and similar materials are placed on top of the tubers to shade them.

Underground structures such as pits, ditches, and clamps also are used for yam storage for limited periods, especially the early varieties, which often are harvested before the end of the rainy season. During construction of pits, the earth dug out is used to build a low wall around the edge. The temperature in the storage space also can be moderated by placing cut vegetation over the ditch, clamp, or pit. In these structures, ventilation and rodent attack of tubers is a major problem, and it is difficult to inspect the tubers. These factors have limited the use of underground pits and clamps on a commercial scale.

Improved Traditional Shelters

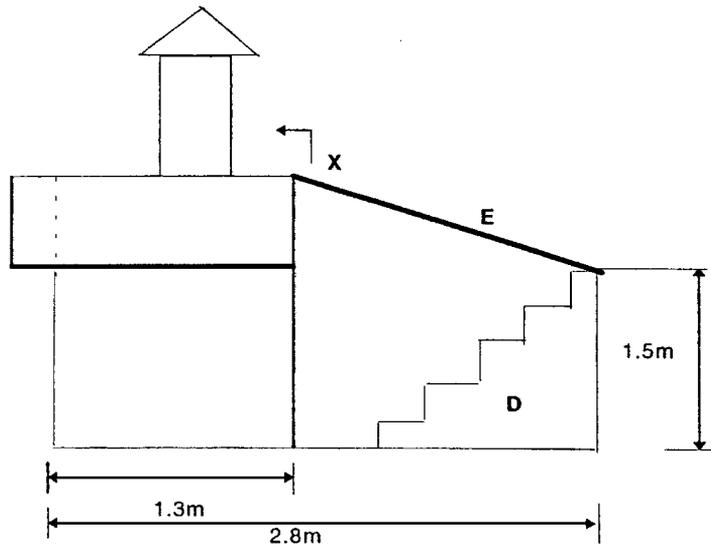
Improved storage structures for yams often are well ventilated, weatherproof, and stronger than traditional shelters. Additional features also may be provided to exclude pests and rodents. A typical improved yam barn has side walls 1.2 m high and wire mesh to ward off rodents and birds [11]. The roof is double-thatched and extended to the eaves with a smooth floor of cement or mud, and only one entry door provided to guard against entry of rodents. Tubers are stored on platforms or shelves. Tubers stored in such improved structures had only 10% spoilage after 5 to 6 months.

An improved pit storage structure has been developed for holding up to 150 tubers [53]. The design (Fig. 2.60) enables low temperatures and high humidities to be maintained, which results in low storage loss and delayed sprouting of tubers. A



- A = DOOR**
- B = MESH**
- C = CHIMNEY**
- D = STAIRCASE**
- E = STAIR COVER**

a. SECTION X - X



b. SECTION Y-Y

Figure 2.60. Experimental pit structure for yam storage. (Source: [53])

large-scale airtight yam house capable of holding 10,000 tubers suitable for rural areas in developing countries has been reported [54]. The room was aerated intermittently to impose an anaerobic environment on the tubers. Tubers were arranged on three-layered wooden racks, and after 5 months in storage both weight loss and microbial decay were minimal.

Refrigerated Stores

Refrigerated stores provide low-temperature and medium- to high-humidity environments for storage. The equipment capacity should be matched with the maximum heat load in the store. Construction materials must be selected to minimize heat gain through the building envelope into the store. Environment-monitoring equipment should be installed to ensure that tuber temperature does not fall below 12 to 15°C to prevent cold-temperature injury. In the design of structural components for yam storage, it also is important to consider equipment and duct work for ventilation and the need for movement of handling equipment for filling and emptying the store. Although the environmental regimes for cold storage of yams have been established, the use of refrigerated storage is very limited. Consequently, there is very limited information on the design and construction of refrigerated cool-store facilities for yams.

2.5.8 Agroprocessing of Yam

Yams usually are marketed as fresh produce. However, tubers also are processed into several food products that are relished in many parts of the tropics. In general, common methods of preparation are boiling, baking, and frying. Boiled and baked yam can be eaten with vegetable sauce or red palm oil. Boiled yam also can be pounded or mashed in mortar and eaten as fufu or utara. Equipment for automatic boiling and mashing of yam into fufu now is available commercially.

Yam cultivars that contain toxic substances such as dioscorene are first sliced and soaked in salt water for several hours before further processing for consumption. These toxic species are used to make toxic bait for fishing and hunting. Industrial processing and utilization of yam includes starch, poultry and livestock feed, and production of yam flour.

Yam flake is one of the common industrial food products of yam (Fig. 2.61). Extensive information on yam-processing methods, equipment, and packaging techniques are available in the literature [7]. Residues from sifting as well as peels represent losses in the energy value of tuber, but they can be used as animal feed. Nutrient losses in yam products obtained from processing can be high, particularly in minerals and vitamins. In products obtained from secondary processing such as biscuits and fufu, the amount of loss depends principally on the amount of edible surface exposed during processing operations. Primary operations such as milling affect the thiamine and riboflavin contents of *D. rotundata*, with average losses of 22% and 37%, respectively. Sun drying results in high losses of B vitamins with little change in mineral content. Pounding yam flour in a traditional wooden mortar or grinding in an electric mixer has similar effects. Losses during culinary preparation of peeled yam can amount to 10% to 15% [7].

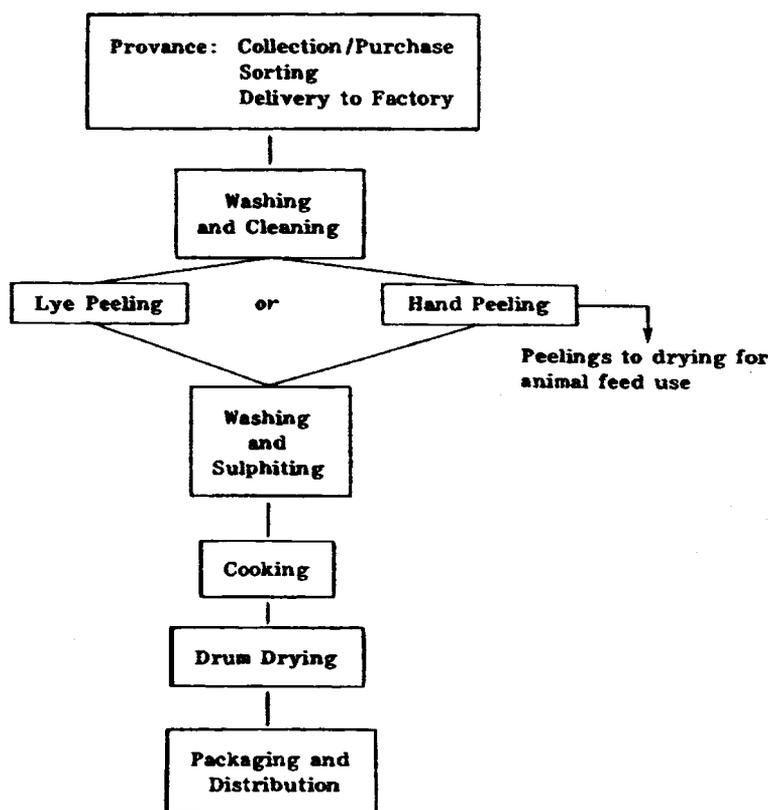


Figure 2.61. Flow diagram for manufacture of yam flake. (Source: [55])

2.5.9 Nutritional, Physicochemical, and Rheological Properties

Nutritional Properties

The nutritional contents of yams vary with species (Tables 2.50 and 2.51). In processed product, the nutritional value is affected by the methods of preparations. Yam tubers have high moisture and dry-matter contents, ranging between 60% and 75% and 25% and 40%, respectively [59]. In general, yams have a high starch (30%) and potassium contents, but the vitamin A content is low (Table 2.52).

Yams contain about 5 to 10 mg·100 g⁻¹ vitamin C, and the limiting essential amino acids are isoleucine and those containing sulphur. Yams contain a steroid sapogenin compound called *diosgenin* that can be extracted and used as a base for drugs such as cortisone and hormonal drugs. Some species contain alkaloids (e.g., dioscorine C₁₃H₁₉O₂N) and steroid derivatives. Proximate composition of different yams has been reported in the literature [10]. Readers can obtain more detailed information on the nutritional values of yam by species and producing region from refs. [10] and [58]. These references also contain information on the effects of method of cooking or preparation on nutritional values of yam products. Yam recipes are also available in the literature [7].

Table 2.50. Summary of proximate analyses of yam tubers

Species	Moisture Content (%)	Carbohydrate (%)	Fat (%)	Crude Protein (%)	Crude Fibre (%)	Ash (%)
<i>D. alata</i> (water yam)	65–73	22–29	0.03–0.27	1.12–2.78	0.65–1.40	0.67–2.06
<i>D. cayenensis</i> (yellow yam)	83	15	0.05	1.02	0.40	0.53
<i>D. rotundata</i> (white yam)	58–73	23	0.12	1.09–1.99	0.35–0.79	0.68–2.56
<i>D. opposita</i>	70–80	16–29	0.06–1.10	1.11–3.10	0.33–1.00	0.69–1.10
<i>D. esculenta</i> (lesser yam)	67–81	17–25	0.04–0.29	1.29–1.87	0.18–1.51	0.50–1.24
<i>D. bulbifera</i> (potato yam)	63–67	27–33	0.04	1.12–1.50	0.70–0.73	1.08–1.51
<i>D. dumetorum</i> (bitter yam)	79	17	0.28	2.78	0.30	0.72
<i>D. hispida</i>	78	18	0.16	1.81	0.93	0.69
<i>D. trifida</i> (cush-cush yam)	—	38	0.44	2.54	—	—

Source: [10].

Physicochemical Properties

Tuber size and shape are variable depending on the species, and both genetic and environmental factors have considerable effects. Tuber size can range from a few centimeters and grams, to 2 to 3 m and over 50 kg. The tubers of most important cultivars are cylindrical in shape, with some roots and growth cracks present; however, some cultivars have an enlarged middle section (Fig. 2.62). The gross morphology of mature tuber includes several layers of cork tissue produced from successive cork cambia forming one beneath another, with the cork cells arranged radially in rows. A ring of meristematic cells, made up of several layers of tangentially elongated, thin-walled cells, lies beneath the cortex (see Fig. 2.26). The parenchyma cells surrounding the vascular bundles contain most of the starch grains (rounded or elliptical). Yams also contain tannin cells, and cells containing bundles of crystals (raphids) also are present. It is widely believed that these crystals are responsible for the itchiness of raw yam tuber and some other root crops when eaten or placed in contact with the skin.

Yam tuber contains about 10% to 20% carbohydrate on a fresh-weight basis, with amylopectin as the main constituent of yam starch [39]. Amylose accounts for 10% to 28% of the starch and influences the starch properties considerably. The iodine binding capacity values of yam starch are directly related to the amylose content (Table 2.53).

Respiration Rates

Respiration rate is a good indicator of metabolic activity in tissue and therefore provides a useful guide to potential storage life. It usually is measured by the rate of O₂ depletion or the rate of CO₂ evolution. Tuber age, degree of physical damage, and spoilage by microorganisms affect the rate of respiration. Yams respire actively at harvest and during sprouting. Respiratory activity is minimal during the period of dormancy

Table 2.51. Nutrient content of yam species per 100-g edible tuber portions

<i>Dioscorea</i> spp.	<i>D. alata</i> (Water Yam)	<i>D. bulbifera</i> (Potato Yam)	<i>D. cayensis</i> (Yellow Yam)	<i>D. dumetorum</i> (Bitter Yam)	<i>D. esculenta</i> (Lesser Yam)	<i>D. rotundata</i> (White Yam)	<i>D. trifida</i> (Cush-Cush Yam)
Water (mL)	65	71	80	67	70	80	80.7
Calories	76 ^a 135	79 ^b 112	71	124	112	71	
Protein (g)	87 2.3	78 1.5	1.5	3.2	102 3.5	1.5	
Fat (g)	1.9 0.1	1.4 0.1	0.1	0.1	1.5 0.1	0.1	2.54
Carbohydrate (g)	0.2 31	0.2 26	0.2	28	0.2 25	16	0.44
Fiber (g)	20 1.5	18 0.9	16	0.8	24 0.5	0.6	38
Calcium (mg)	0.6 28	1.2 69	0.6	52	0.6 62	36	8
Phosphorous (mg)	38 52	40 29	36	45	12 53	17	38
Iron (mg)	28 16	58	17	35	35	5.2	0.52
Vitamins	1.1	2.0	5.2		0.8		
β -carotene equivalent (μ g)	10	10					
Thiamine (mg)	0.11	0.05			0.10		
Riboflavin (mg)	0.02	0.03			0.01		
Niacin (mg)	0.3	0.04			0.8		
Ascorbic acid (mg)	6	0.5			15		

Adapted from [24, 56–58].

^a Two values reported.

^b Bulbil or aerial tuber.

Table 2.52. Nutritional values of yam tuber

Nutrient	Amount per 100-g Edible Portion
Calories	71.00–135.00
Moisture (%)	81.00–65.00
Protein (g)	1.40–3.50
Fat (g)	0.40–0.20
Carbohydrate (g)	16.40–31.80
Fiber (g)	0.40–10.00
Ash (g)	0.60–1.70
Calcium (mg)	12.00–69.00
Phosphorous (mg)	17.00–61.00
Iron (mg)	0.70–5.20
Sodium (mg)	8.00–12.00
Potassium (mg)	294.00–397.00
β -Carotene equivalent (mg)	0.00–10.00
Thiamin (mg)	0.01–0.11
Riboflavin (mg)	0.01–0.04
Niacin (mg)	0.30–0.80
Ascorbic acid (mg)	4.00–18.00

Table 2.53. Physicochemical properties of yam starch fraction

	Amylose				Amylopectin			
	<i>D. alata</i>	<i>D. cayenensis</i>	<i>D. dumetorum</i>	<i>D. rotundata</i>	<i>D. alata</i>	<i>D. cayenensis</i>	<i>D. dumetorum</i>	<i>D. rotundata</i>
IBC (%)	19.88	19.86	19.89	19.84	0.64	0.76	0.72	0.67
β -amylolysis (%)	92.3	94.7	97.5	95.8	59.6	65.4	66.7	60.5
Molecular weight (triacetate) $\times 10^{-5}$	2.65	2.10	2.2	2.3	—	—	—	—
Viscosity (n)	1.98	1.85	1.88	1.93	2.18	2.38	2.75	2.32
Average chain length	—	—	—	—	22	21	24	19
% Yield (based on starch)	24.5	22.9	23.8	22.2	74.2	75.6	73.4	76.7

Sources: [61, 62].

[63]. Rates of respiration can vary from 5 to 20 mL CO₂·kg⁻¹ fresh weight·hr⁻¹ in healthy tuber (*D. rotundata*) to over 35 mL CO₂·kg⁻¹ fresh weight·hr⁻¹ in decaying tuber [64]. Respiration rates of yam tubers are important in the design of storage structures and their environmental control facilities. Respiration data also are useful in the design of modified-atmosphere packaging and coating of tubers with waxes to extend their shelf life.

Respiratory weight loss contributes significantly to total storage loss (Table 2.54). Yams stored for 5 months may lose up to 10% of dry-matter content through respiration [65]. During storage, the increase in both heat of respiration and heat load is greater at high initial store temperatures. Under tropical conditions (15–35°C), the heat of respiration can account for up to 89% to 100% of the total heat load, especially if the tubers are free

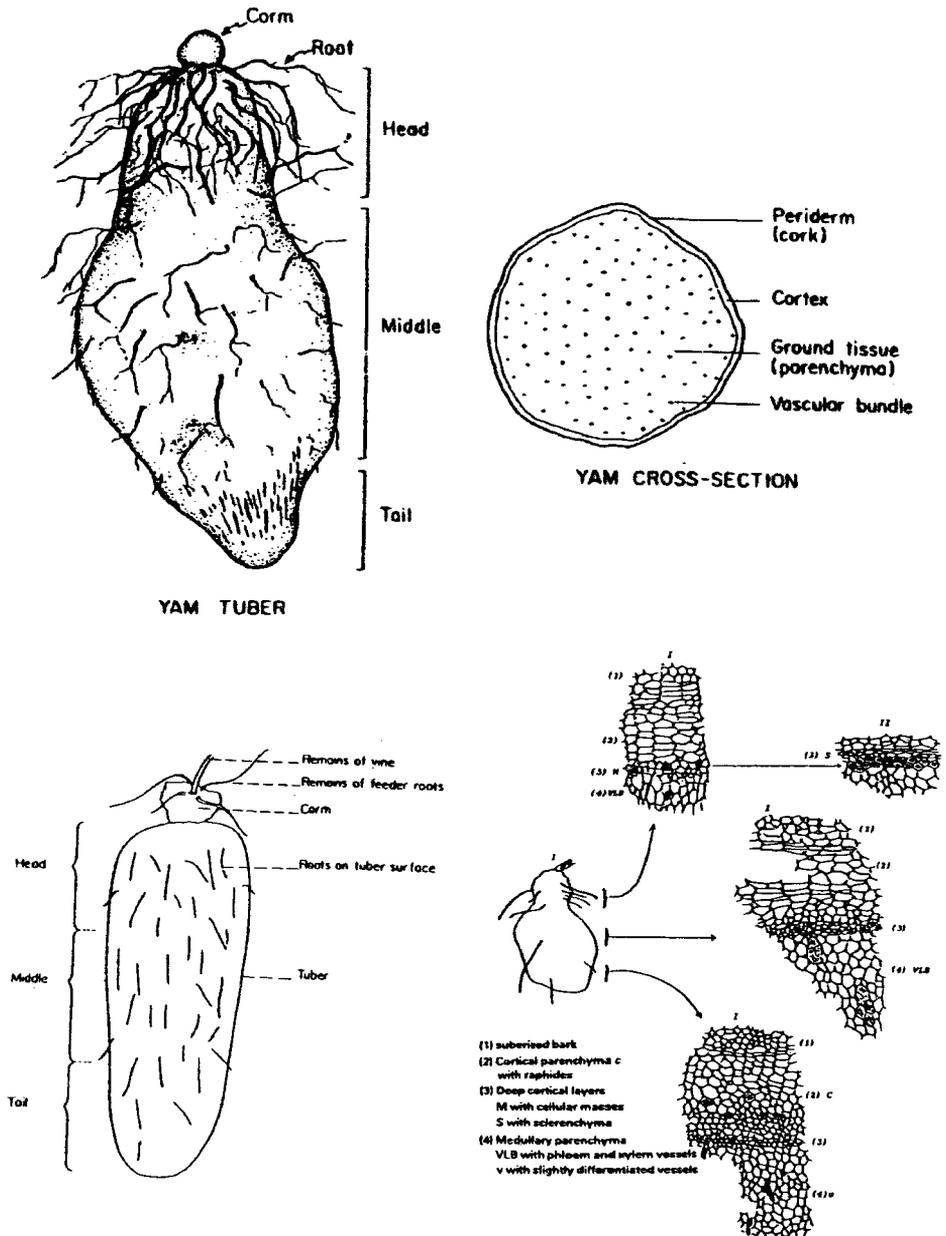


Figure 2.62. Morphology and anatomy of yam tuber. I, fifth month; II, ninth month. (Sources: [2, 17, 60])

Table 2.54. Relative contribution of respiration to total weight loss of yam tubers during storage

	Total Daily Weight Loss (%)		Daily Weight Loss due to Respiration	
	25°C	35°C	25°C	35°C
After harvest	0.22 ± 0.02	0.36 ± 0.02	0.058	0.108
Dormant	0.15 ± 0.03	0.28 ± 0.06	0.011	0.028
Sprouting	0.21 ± 0.02	0.34 ± 0.07	0.074	0.068

Source: [63].

Table 2.55. Linear regression equations of storage air temperature and storage time (X in hours)

Initial Storage Temperature (°C)	Regression Equation	Correlation Coefficient
15	16.24 + 0.131X	0.96
20	20.97 + 0.176X	0.98
25	24.27 + 0.171X	0.98
30	29.82 + 0.194X	0.99
35	32.98 + 0.1217X	0.98

Source: [63].

from infection by mold and other microorganisms [59]:

$$Q_p = 0.021 + 4.247Q_r$$

where Q_p is the heat load of respiration and Q_r is the heat of respiration ($R = 0.99$).

The storage air temperature also can be predicted for different initial storage temperatures (Table 2.55).

Thermophysical and Rheological Properties

The thermophysical and rheological properties of yam products are important for the design of handling and processing operations. They are also useful in predicting starch behavior during cooking and cooling processes, and they often highlight the modification required to obtain required product specifications. Some of the relevant properties include specific heat capacity of the tuber, size of starch granules, viscosity, and gelatinization temperature. The specific heat of yam tuber can be estimated from Siebel's equation based on the moisture content [66]:

$$S = 0.0335 \times [\% \text{ H}_2\text{O in food}] + 0.8370 (\text{kJ} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1})$$

Yam tubers have high moisture content, usually above 60% of fresh tuber weight. For design purposes, an average moisture content of about 73.5% is recommended [31].

The range of size of starch granules and their gelatinization temperatures for a number of economically important yam species have been reported (Table 2.56). Based on size and form, the granules of yam starch from the different species may be classified into

Table 2.56. Starch granule size and gelatinization temperatures of yams

Species	Granule Size (μ)	Gelatinization Temperature ($^{\circ}$ C)
<i>D. alata</i>	5–50	69.0–78.5
<i>D. rotundata</i>	5–45	64.5–75.5
<i>D. cayenensis</i>	3–25	71.0–78.0
<i>D. opposita</i>	5–60	65.5–75.5
<i>D. bulbifera</i>	5–45	72.0–80.0
<i>D. esculenta</i>	1–15	69.5–80.5
<i>D. hispida</i>	1–5	75.5–83.0
<i>D. dumetorum</i>	1–4	77.0–85.5
<i>D. trifida</i>	10–65	—

Sources: [10, 61].

Table 2.57. Starch characteristics of yam species

Examples of Species	Starch Characteristics
<i>D. alata</i> , <i>D. rotundata</i> , <i>D. opposita</i>	Fairly large granules, oval or egg-shaped, elongated rounded squares, or mussel shell-shaped, sometimes with one side flattened
<i>D. bulbifera</i> , <i>D. cayenensis</i>	Many fairly large granules, of rounded triangular form, sometime elongated, rarely trapezoidal form
<i>D. esculenta</i> , <i>D. hispida</i> , <i>D. dumetorum</i>	All granules small, rounded or polyhedral, sometimes complex, as though built up from many smaller granules
<i>D. digitata</i> , <i>D. sinuata</i> , <i>D. belizensis</i>	All granules small, rounded in form, often joined together at one or more surfaces; starches of this group are very similar to cassava or sweet potato starches

Sources: [67].

four groups (Table 2.57). In general, starch granules of *D. rotundata*, *D. cayenensis*, and *D. alata* are large (up to 50 μ m), whereas those of *D. esculenta* and *D. dumetorum* are much smaller (1–5 μ m). Other rheological properties of yams also vary among the species (Table 2.58).

Although the small grains are far more numerous than larger ones, they only account for a small percentage of the total mass of the starch content (Fig. 2.63).

The viscosity of yam starches varies with species. Results of measurement using several yams produced in West Africa showed that viscosity fell appreciably with a rise in starch temperature following heating (Table 2.59).

A transition temperature of 77.5 $^{\circ}$ C with maximum viscosity of 290 Braebender units (BU) has been reported for yam starch using the Braebender amylograph [69]. A high viscosity maximum of 470 to 690 BU for *D. rotundata* has been measured, compared with 100 to 200 BU for *D. alata*, 55 BU for *D. esculenta*, and 25 BU for *D. dumetorum* [70]. The starches of *D. rotundata* and *D. alata* have high gel strength compared with the other species. Starch properties vary among parts of the tuber, with the largest granules

Table 2.58. Some rheological properties of yam starches

	<i>D. alata</i>	<i>D. rotundata</i>	<i>D. cayenensis</i>	<i>D. bulbifera</i>	<i>D. esculenta</i>	<i>D. dumetorum</i>
Viscosity (BU)	150	720	220	40	65	120
Intrinsic viscosity (n)	3.05	3.13	2.98	—	—	3.15
Absolute density (g · mL ⁻¹)	1.513	1.511	1.519	—	—	1.509
Water-binding capacity (%)	99.4	98.6	99.8	—	—	97.4
Iodine-binding capacity (%)	4.69	4.72	4.56	—	—	4.95
Gelatinization temperature (°C)	88.0	77.5	90.5	89.0	79.0	85.0
Gelatinization temperature ^a (°C)	65–71.5 69 ^b	63.5–71 66 ^b	68–74.5 (72)	—	—	65.5–72.5 68 ^b

Modified from [10, 61].

^a Recorded temperatures correspond to loss of birefringence by 2%, 50%, and 98% of the starch granules.

^b Mean.

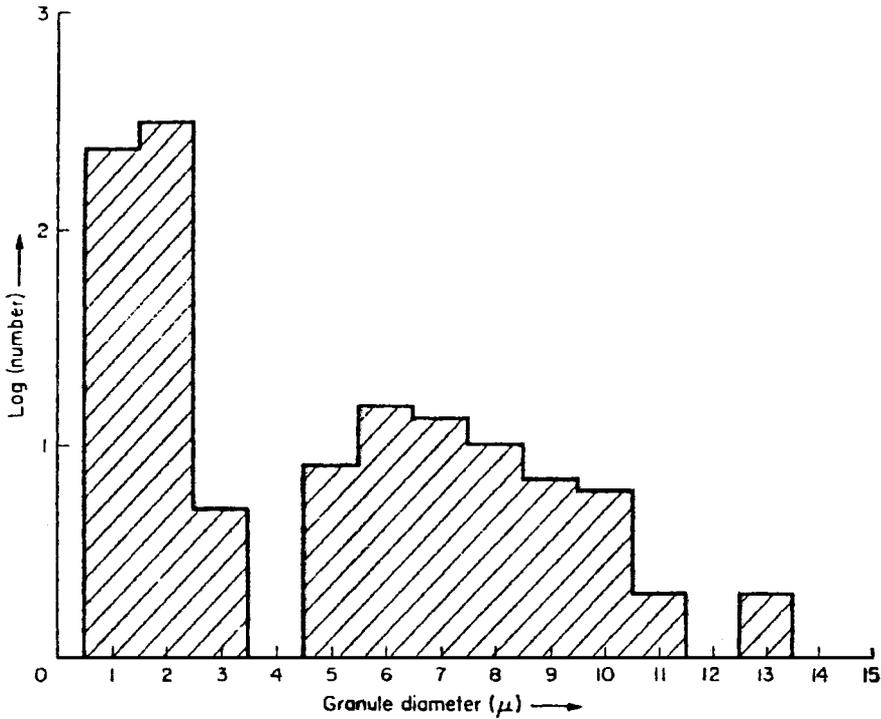


Figure 2.63. Particle size distribution of *D. esculenta* starch. (Source: [10])

Table 2.59. Viscosity characteristics of yam starches in West Africa

Species	Viscosity (BU)	Gelatinization Temperature (°C)
<i>D. alata</i>	150	88.0
<i>D. rotundata</i>	720	77.5
<i>D. cayenensis</i>	220	90.5
<i>D. bulbifera</i>	40	89.0
<i>D. esculenta</i>	65	79.0
<i>D. dumetorum</i>	120	85.0

Source: [68].

Table 2.60. Swelling power and solubility of yam starches

Temperature (°C)	Swelling Power (%)				Solubility (%)			
	<i>D. alata</i>	<i>D. cayenensis</i>	<i>D. dumetorum</i>	<i>D. rotundata</i>	<i>D. alata</i>	<i>D. cayenensis</i>	<i>D. dumetorum</i>	<i>D. rotundata</i>
60	5.01	8.25	7.38	3.10	2.70	1.30	2.64	1.80
70	7.05	9.88	8.96	7.50	3.50	2.40	4.35	4.21
80	11.50	11.97	12.15	12.55	4.55	4.25	7.02	6.05
90	15.45	14.83	15.52	16.50	6.98	7.90	7.02	6.05
95	20.50	16.90	18.65	21.50	7.80	13.80	16.80	11.90

Source: [61].

Table 2.61. Swelling and gelatinization attributes of yam starches

Species	Pasting Temperature ^a (°C)	Maximum Viscosity ^a (BU)	Period of Increasing Viscosity ^a Increase	Apparent Rate of Viscosity	At 95°C	
					Swelling	Critical Concentration Value
<i>D. rotundata</i>	73.5	980	22.5 min	2.3	24.9	4.0
<i>D. esculenta</i>	78.5	500	Steadily increasing		23.0	4.3
<i>D. cayenensis</i>	75.0	690	16.5 min	2.4	21.3	4.7
<i>D. alata</i>	77.5	620	Steadily increasing		18.3	5.5
<i>D. dumetorum</i>	83.0	185	Steadily increasing		13.9	7.2

Source: [73].

^a Data obtained from Braebender viscosograph curves.

located in the central portions of the tuber. In general, the viscosities of some yam starches are relatively low, especially for species such as *D. hispida* and *D. anguina* [71]. This factor, in addition to the high costs of production, has limited the commercial exploitation of yam starches for industrial application.

In general, most yam starches create viscous pastes with high gel strengths compared with the starches of other tropical starch crops [72]. These rheological properties are related to the swelling and solubility attributes (Tables 2.60 and 2.61) of the starch

Table 2.62. Effects of cooking on yam

	Cooking Time	White Yam			Yellow Yam			Water Yam		
		Head	Middle	Tail	Head	Middle	Tail	Head	Middle	Tail
Starch release (mg·g ⁻¹ fresh weight)	3 min	8.0	9.0	6.5	6.0	5.5	5.0	6.5	7.0	6.0
	5 min	9.0	10.0	7.5	6.5	6.5	5.8	7.0	7.0	6.5
	7 min	11.0	11.0	8.5	8.5	8.5	7.5	8.3	7.5	6.8
	10 min	10.0	9.0	9.5	9.5	9.5	8.0	9.0	7.5	7.0
Compressive strength (N·cm ⁻¹)	3 min	12.2	11.4	10.8	12.8	10.8	11.8	10.4	10.0	10.4
	5 min	9.8	8.1	8.4	11.4	8.4	8.0	9.1	8.1	9.0
	7 min	8.3	5.4	4.8	8.8	8.0	7.8	8.7	5.8	5.6
	10 min	7.2	4.6	3.6	7.6	6.5	7.0	6.2	5.6	4.7

Source: [75].

Table 2.63. Rheological properties of yam (*D. rotundata*) dough at 15 minutes after reconstitution

Steam Pressure (Psig)	Modulus of Elasticity ($\times 10^5$ dyne·cm ⁻²)	Ultimate Yield Deformation	Recoverable Elasticity (%)	Energy Ratio
0	5.2	0.50	66	0.77
5	4.9	0.48	73	0.71
10	4.4	0.45	81	0.55

Source: [76].

[61, 63], and also to the size of granules [74]. The consistency of yam food products such as fufu or eba is related to the pasting properties of yam starches. Consistency rises continually during the heating cycle and steadily during the holding period, with no distinct peak height as is usually observed with wheat and a number of other cereals [39]. Yam starches show increased swelling and solubility properties and stable hot-paste consistency at high temperatures.

Thermomechanical Properties

Cooking and reconstitution affect the mechanical indices of texture in yam products. It has been shown that differences in texture were related to changes in the starch granules after cooking [39], and the compressive strength of cooked yam discs was correlated with the amount of starch released during cooking (Table 2.62). The degree of starch damage also affected the modulus of elasticity, ultimate deformation, recovery elasticity, and energy loss ratio of yam flakes (Table 2.63). These results also were affected by the steam pressure in cooking for both reconstituted and dried product (Table 2.64).

In comparison with the other principal yam species, *D. rotundata* has significantly higher viscosity, and the gel strengths were also moderately high (Table 2.65). These engineering properties partly explain the preference for *D. rotundata* in the production of foods in which a stiff dough is required, such as fufu in West Africa.

Table 2.64. Influence of cooking conditions on properties of dried yam (*D. rotundata*) product

Steam Pressure (Psig)	Powder Bulk Density (g·cm ⁻³)	Starch Damage (BVI)	Swelling Power (cm ³ ·g ⁻¹ solids)	Solubility (g·cm ⁻³ water)
0	0.31 ± 0.05	70 ± 2	11.7	2.4
5	0.30 ± 0.07	100 ± 3	11.7	2.6
10	0.28 ± 0.03	110 ± 1	13.2	3.1

Source: [76].

Table 2.65. Rheological properties of various yam starches

Species/Cultivar	Pasting Temperature (°C)	Viscosity (BU)		Gel Strength (mL)		
		On Attaining 95°C	Maximum Reached Before Cooling	After 24 h	After 96 h	After 168 h
<i>D. rotundata</i>						
Puna	78	450	630	8.8	13.6	14.1
Labreko	78–79	260	470	4.3	6.2	8.0
Kplinjo	77	330	490	10.6	12.7	13.3
Tantanpruka	79	610	650	12.4	17.2	20.5
Tempi	80–92	430	520	7.5	10.5	10.8
<i>D. alata</i>						
White-fleshed	85	25	110	14.8	16.5	17.2
Purple-fleshed	81	80	200	14.8	18.5	19.4
<i>D. esculenta</i>	82	25	55	2.5	4.0	4.6
<i>D. dumetorum</i>	82	25	25	—	—	—

Source: [70].

References

1. Martin, F. W., ed. 1984. *HandBook of Tropical Food Crops*. Boca Raton, FL: CRC Press.
2. Yamaguchi, M. 1983. *World Vegetables: Principles, Production and Nutritive Values*. Westport, CT: AVI Publishing Company.
3. Thompson, A. K. 1996. *Postharvest Technology of Fruit and Vegetables*. London: Blackwell Science.
4. FAO. 1975. *Production Yearbook*. Rome: Author.
5. FAO. 1991. *Production Yearbook for 1990*. Rome: Author.
6. FAO. 1992. *Production Yearbook for 1991*. Rome: Author.
7. Bencini, M. C. 1991. Post-harvest and processing technologies of African staple foods: A technical compendium. FAO Agricultural Service Bulletin 89. Rome: FAO.
8. Dorosh, P. 1988. The economics of root and tuber crops in Africa. RCMP Research Monograph. Ibadan, Nigeria: IITA.
9. National Academy of Sciences. 1978. *Post-harvest Food Losses in Developing Countries*. Washington, DC: Author.

10. Coursey, D. G. 1967. *Yams*. London: Longmans-Green.
11. Akoroda, M. O., and S. K. Hahn. 1995. Yams in Nigeria: Status and trends. *African Journal of Root and Tuber Crops* 1(1):38–41.
12. Gooding, H. J. 1960. West Indian *Dioscorea alata* cultivars. *Tropical Agric. Trinidad* 37(1):11–30.
13. Burton, C. L. 1970. Diseases of tropical vegetables on the Chicago market. *Tropical Agric. Trinidad* 47:303–313.
14. Sobulo, R. A. 1972. Studies on white yam (*Dioscorea rotundata*): I. Growth analysis. *Expt. Agric.* 8:99–106.
15. Njoku, E., C. Oyolu, S. N. C. Okonkwo, and F. I. O. Nweke. 1973. The pattern of growth and development in *Dioscorea rotundata* Poir. Third International Symposium on Tropical Root Crops. Ibadan, Nigeria: IITA.
16. Onwueme, I. C. 1977. Field comparison of West African planting and harvesting practices in yam (*Dioscorea rotundata*): Pre-sprouting, dry season planting, and double-harvesting. *J. Agric. Sci.* 84:503–505.
17. Onwueme, I. C., and W. B. Charles. 1994. Tropical root and tuber crops: Production, perspectives and future prospects. FAO Plant Production and Protection Paper 126. Rome: FAO.
18. Gregory, L. E. 1968. Factors that influence vegetative bud development in rootstock segments of *D. floribunda* and *D. composita*. *J. Agric. Univ. Puerto Rico* 52:155–163.
19. Martin, F. W., F. K. S. Foo, and J. Cuevas. 1974. Stimulation of yam (*Dioscorea*) tuber growth by gamma irradiation. *J. Amer. Soc. Hort. Sci.* 99:282–284.
20. Nystrom, L. W., J. E. Shrum, and R. F. Dawson. 1973. A mechanical harvester for *Dioscorea composita*. 3rd Int. Symp. Trop. Root Crop, Ibadan, Nigeria.
21. Mozie, O. 1996. Effect of mechanical injury and regulated air flow on storage losses of white yam tubers. *Trop. Sci.* 36:65–67.
22. McGregor, B. M. 1987. Tropical products transport handbook. U.S. Department of Agriculture, Agriculture Handbook No. 668.
23. Thompson, A. K., B. O. Been, and C. Perkins. 1977. Fungicidal treatment of stored yams. *Tropical Agric. Trinidad* 54:179–183.
24. Kay, D. E. 1973. *Crop and Product Digest 2: Root Crops*. London: Tropical Products Institute.
25. Tindall, H. D. 1983. *Vegetables in the Tropics*. London: MacMillan Press.
26. Coursey, D. G. 1961. The magnitude and origin of storage losses in Nigerian yams. *J. Sci. Food Agric.* 12(8):574–580.
27. Thompson, A. K., B. O. Been, and C. Perkins. 1973. Reduction of wastage in stored yams. In *Proc. 3rd Symp. Int. Soc. Tropical Root Crops*, pp. 443–449. Ibadan, Nigeria: IITA.
28. SeaLand. 1991. The shipping of perishables, Sealand's commitment to excellence. Elizabeth, NJ: SeaLand Service.
29. Gonzales, M. A., and A. C. de Rivera. 1972. Storage of fresh yams (*D. alata* L.) under controlled conditions. *J. Agric. Univ. Puerto Rico* 56:46–56.

30. *Guide to Food Transport: Fruit and Vegetables*. 1989. Mercantilia Publishers.
31. Hardenburg, R. E., A. E. Watada, and C. Y. Wang. 1986. The commercial storage of fruits, vegetables, and florist and nursery stocks. U.S. Department of Agriculture, Agriculture Handbook No. 66 (revised).
32. Thompson, A. K. 1996. *Postharvest Technology of Fruit and Vegetables*. London: Blackwell Science.
33. Coursey, D. G. 1968. Low temperature injury in yams. *J. Food Technology* 3:143–150.
34. Czyhrinciw, N., and W. Jaffe. 1951. Modificacions quimicas durante la conservacion de raices tuberculos. *Archos Venez. Nutr.* 2(1):49–67.
35. Safeway Stores, Inc. 1986. *Transit and Storage Properties of Produce Commodities*. Newark, DE: Produce Marketing Assoc.
36. Imakawa, S. 1967. Browning of Chinese yam (*D. batatas*). *Hokkaido Daigaku Hobun Kiyo* 6:445–447.
37. Lang, G. A. 1987. Dormancy: A new universal terminology. *HortScience* 22:815–820.
38. Passam, H. C., and R. A. Noon. 1977. Deterioration of yams and cassava during storage. *Ann. Appl. Biol.* 85:436–440.
39. Osagie, A. U. 1992. *The Yam Tuber in Storage*. Benin City, Nigeria: Postharvest Research Unit, Department of Biochemistry, University of Benin.
40. Campbell, J. S., V. O. Chukwueke, F. A. Teriba, and H. V. S. Ho-a-shu. 1962. Some physiological experiments with the white Lisbon yam (*Dioscorea alata* L.): I. The breakage of the rest period in tubers by chemical means. *Emp. J. Exp. Agric.* 30(118):108–114.
41. Onwueme, I. C. 1975. Influence of storage time on earliness of sprouting and tuberizing in *Dioscorea rotundata* yams. *J. Agric. Sci. Camb.* 84:503–505.
42. Nwoke, F. I. O., and S. N. C. Okonkwo. 1981. Length of tuber dormancy in yam (*D. spp.*). *Nigerian J. Agric. Sci.* 3:153–156.
43. Hayward, L. A. W., and H. M. Walker. 1961. The effect of pre-harvest foliar spraying with maleic hydrazide on the storage of yams. *Ann. Rep. West Afr. Stored Products Res. Unit*, pp. 107–115.
44. Passam, H. C. 1982. Dormancy in yams in relation to storage. In *Yams—Ignames*, ed. J. Miegé and S. N. Lyonga, pp. 285–293. Oxford: Clarendon Press.
45. Onwueme, I. C. 1973. The sprouting process of yam (*D. spp*) tuber pieces. *J. Agric. Sci. Camb.* 81:375–379.
46. Ireland, C. R., W. W. Schwabe, and D. G. Coursey. 1981. The occurrence of batatasins in the Dioscoreaceae. *Phytochemistry* 20:1569–1571.
47. Adesuyi, S. A. 1982. Application of high technology to the improvement of yam storage. In *Yams—Ignames*, ed. J. Miegé and S. N. Lyonga, pp. 312–319. Oxford: Clarendon Press.
48. Adesuyi, S. A. 1978. Progress in food irradiation: Nigeria food irradiation. *Inform* 9:47.
49. Adesuyi, S. A. 1976. The use of radiation for control of sprouting and improving the food qualities of yams *Dioscorea* spp., part of a co-ordinated programme on

- the shelf-life extension of irradiated fruits and vegetables. Final Report, Int. Atomic Energy, Vienna (IAEA-R-1506-F).
50. Adesiyun, S. O. 1977. Studies on the effects of gamma radiation (from Cobalt 60 source) on storage life of white yam (*Dioscorea rotundata* var. *efon*) infected with *Scutellonema bradys*. *Ann. Appl. Biol.* 86:213–218.
 51. Ng, S. Y. C. 1991. Virus-free yam (*Dioscorea rotundata* Poir): Distribution methods. In *Proc. 9th Int. Soc. Trop. Root Crops*, Accra, Ghana.
 52. Wilson, J. E., and L. Victor. 1980. Relationships between seedlings and their vegetative progenies in white yam (*D. rotundata*). *INRA Int. Seminar on the Yam 1981*, pp. 269–278.
 53. Ezeike, G. O. I. 1985. Experimental analysis of yam (*D. spp.*) tuber stability in tropical storages. *Trans. ASAE* 28:1641–1645.
 54. Osuji, G. O. (ed.) 1987. The manipulation of the carbohydrate metabolism of the yam tuber to prolong its storage life and induce uniformity of sprouting. *Advances in Yam Research 2*.
 55. Coursey, D. G. 1983. Yams. In *HandBook of Tropical Foods*, ed. H. T. Chan, pp. 555–601. New York: Marcel Dekker.
 56. FAO. 1968. *Food Composition Table for Use in Africa*. Rome: Author.
 57. FAO. 1972. *Food Composition Table for Use in East Asia*. Rome: Author.
 58. Bradbury, J. H., and W. D. Holloway. 1988. *Chemistry of Tropical Root Crops: Significance for Nutrition and Agriculture in the Pacific*. Canberra, Australia: Australian Centre for International Agricultural Research.
 59. Alakali, S. E. Obeta, and O. Ijabo. 1995. Heat of respiration of yam tubers and its effects on heat load. *African Journal of Root and Tuber Crops* 1(1):31–35.
 60. Degras, L. 1983. *The Yam: A Tropical Root Crop*. London: The MacMillan Press.
 61. Emiola, L., and L. C. Delarosa. 1981. Physicochemical characteristics of yam starches. *J. Food Biochem.* 5:115–130.
 62. Whelan, W. J. 1964. Hydrolysis with B-amylase and preparation of the -amylase limit dextrin of amylopectin. In *Methods of Carbohydrate Chemistry*, vol. IV, ed. R. L. Whistler, pp. 261–266. New York: Academic Press.
 63. Passam, H. C., S. J. Read, and J. E. Rickard. 1978. The respiration of yam tubers and its contribution to storage loss. *Trop. Agric.* 55:207–214.
 64. Coursey, D. G., and J. D. Russul. 1969. A note on endogenous and biodeteriorative factors in the respiration of dormant yam tubers. *Int. Biodeterioration Bull.* 5:27–30.
 65. Coursey, D. G., and H. M. Walker. 1960. A study of the origins of weight loss in stored yams. *Rep. West Afr. Stored Prod. Res. Unit*, pp. 61–64.
 66. Siebel, J. E. 1892. Specific heat of various products. *Ice and Refrigeration* 2:256–257.
 67. Seidmann, J. 1964. Mikroskopische untersuchung verschiedener Dioscorea-starken. *Starke* 16:246–253.
 68. Greenwood-Barton, L. H. 1961. Yam starches from Nigeria. Report No. 51 of the Tropical Products Institute, London.
 69. Hollo, J. 1964. L'utilisation industrielle de l'igname. Paper presented to the 1st

- Congres Internationale des Industries Agricoles et Alimentaires des Zones Tropicales et Sub-tropicales, Abidjan.
70. Rasper, V., and D. G. Coursey. 1967. Properties of starches of some West African yams. *J. Sci. Food Agric.* 18:240–244.
 71. Rao, P. S., and R. M. Beri. 1952. Tubers of *Dioscorea hispida* Dennst. *Indian Forester* 78(3):113–133.
 72. Rasper, V. 1969. Investigations on starches from major starch crops grown in Ghana: I. Hot paste viscosity and gel forming powder. *J. Sci. Food Agric.* 20:165–171.
 73. Rasper, V. 1969. Investigations on starches from major starch crops grown in Ghana: II. Swelling and solubility patterns; amyclastic susceptibility. *J. Sci. Food Agric.* 20:642–646.
 74. Rasper, V. 1971. Investigations on starches from major starch crops grown in Ghana: III. Particle size and particle size distribution. *J. Sci. Food Agric.* 22:572–580.
 75. Onayemi, O. R. O. Babalola, and A. Badanga. 1987. Textural properties of cooked tropical yam (*D. spp.*). *J. Texture Studies* 18:17–29.
 76. Ayernor, G. S. 1976. Particulate properties and rheology of pregelled yam (*Dioscorea rotundata*) products. *J. Food. Sci.* 41:180–182.

2.6 Storage of Edible Aroids

Linus U. Opara

2.6.1 General

Terminology and Scope

The aroids (family *Araceae*) contain many food crops grown in several tropical and subtropical countries (Table 2.66). The most important edible aroids are the *taro* or cocoyam (*Colocasia esculenta*) (Fig. 2.64) and tannia or new cocoyam (*Xanthosoma sagittifolium*) (Fig. 2.65), which together are called *cocoyams* in many parts of the world, especially in Africa. For the purpose of this sections, the terminology *edible aroids* is be used to include the cocoyams and other edible members of the Aracae family. If distinction is necessary to highlight differences in storage and other attributes of the two most important edible aroids, the term *taro* is used for *Colocasia* and *tannia* for *Xanthosoma*.

Because of their great economic importance compared with other types of edible aroids, the information covered in this article is based on these two edible aroids. It is important to note that *Alocasia cyrtosperma* and *Amorphophallus* spp. are cultivated globally to a very limited extent, and they are important food crops in some parts of India, Southeast Asia, and the Pacific Islands [2].

Economic Importance

These aroids are cultivated in the lowland humid areas and contribute an important part to the carbohydrate content of the diet in these regions. They produce edible starchy storage corms or cormels. Although the edible aroids are less important than other tropical root crops such as yam, cassava, and sweet potato, they are still a major staple in

Table 2.66. Types of edible aroids

Botanical Name	Common Names	Comments
<i>Colocasia esculenta</i> (L.) Schott	Taro, malanga, old cocoyam, eddoe, gabi, dasheen, ede	The term "taro" has also been used to refer to the edible aroids in general
<i>Xanthosoma</i> spp.	Tannia, ede, new cocoyam	<i>X. sagittifolium</i> is the most important, while <i>X. atrovirens</i> , <i>X. violaceum</i> , and <i>X. carau</i> are of lesser importance
<i>Alocasia</i> spp.	Giant taro	Includes <i>A. macrorrhiza</i> as the main cultivated species and <i>A. indica</i> , <i>A. fornicata</i> , and <i>A. cucullata</i> as minor species
<i>Cyrtosperma chamissonis</i>	Swamp taro	—
<i>Amorphophallus campanulatus</i>	Elephant yam	<i>A. concophyllus</i> , <i>A. varialbis</i> , and <i>A. rivieri</i> are also edible

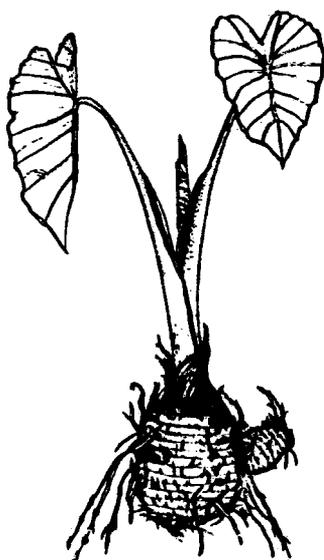


Figure 2.64. Taro (*Colocasia esculenta*) plant. (Source: [1])

some parts of the tropics and subtropics. In the South Pacific region in particular, aroids represent a very high proportion of the root crops.

World production of edible aroids is difficult to estimate because of the subsistence nature of agriculture in fragmented landholdings in the producing areas. Estimated world production in 1988 was around 5.5 million ton, constituting about 3.3% of all root crops [3, 4]. Total world production area of taro alone was estimated to be about 993×10^3 ha in 1983, with 80% in Africa [5]. During this period, global production of taro was 5.607 million ton, with about 61.33% in Africa and 38.67% in Asia.



Figure 2.65. Tannia (*Xanthosoma sagittifolium*) plant. (Source: [1])

Current estimates indicate that total world production of the major edible aroids (taro and tannia) is about 5.23 million ton in an area of 983 million ha, with average yield of 5314 kg·ha⁻¹ [6]. Production declined by 5.3% from 5.64 million ton in the period from 1979 through 1981 to 5.34 million ton in 1989.

In the South Pacific and parts of Africa, taro is a staple food, and in the Caribbean and West Africa in particular tannia is the main edible aroid. Despite the importance of edible aroids as a food source, there is comparatively little scientific information on their storage physiology, and thus there is very limited application of modern and improved storage technology to extend both storage and shelf life. Perhaps the dearth of sustained research on postharvest physiology and response of edible aroids to new storage technologies is partly due to the fact that these crops can be grown year-round in tropical regions depending on the availability of water.

Nutritional Value

Aroids are grown chiefly for domestic consumption or sale in local markets, as the possibilities for export are limited by their short postharvest life. In some warm regions, however, improved postharvest techniques and availability of air freight are increasing the export potential of edible aroids. The mature corms, young shoots, and leaves of edible aroids are used mostly as boiled vegetables. The corms also are roasted, baked, or fried and frequently processed into flour such as fufu in Nigeria. In the southeastern part of Nigeria, tannia is used in small quantities as soup thickener after boiling and pounding in the mortar to obtain a consistent paste. In addition to their high starch content, edible

Table 2.67. Nutritional values of the major edible aroids per 100-g edible portion.

	Taro (<i>Colocasia esculenta</i>)			Tan(n)ia (<i>Xanthosoma saggitifolium</i>)		
	Corms	Corms	Leaf Stalks	Corms	Leaves	Shoots
Major nutrients						
Water	73	75	93	65	89	89
Calories	102	94	24	133	34	33
Protein (g)	1.8	202	0.5	2.0	2.5	3.1
Fat (g)	0.1	0.4	0.2	0.3	1.6	0.6
Carbohydrate (g)	23	21	6	31	5	5
Fiber (g)	1.0	0.8	0.9	1.0	2.1	3.2
Calcium (mg)	51	34	49	20	95	49
Phosphorous (mg)	88	62	25	47	388	80
Iron (mg)	1.2	1.2	0.9	1.0	2.0	0.3
Vitamins						
β -carotene equivalent (μ g)	Trace	Trace	180	Trace	3300	—
Thiamine (mg)	0.10	0.12	0.02	0.10	—	—
Riboflavin (mg)	0.03	0.04	0.04	0.03	—	—
Niacin (mg)	0.8	1.0	0.4	0.5	—	—
Ascorbic acid (mg)	8	8	13	10	37	82

Compiled from [10–13].

aroids have a higher content of protein and amino acids than many other tropical root crops [7, 8]. Protein quality is essentially the same for all aroids, determined with lysine as the first limiting amino acid (chemical score 57–70) [9].

The nutritional values of the major edible aroids are presented in Table 2.67. A summary of comprehensive chemical analyses of large samples of aroids from different countries also is presented (Table 2.68), as well as the highlights of the nutritional and chemical composition (Table 2.69). This information may be used directly by food scientists and engineers in developing improved food-processing operations and new food products. The large variability of composition of root-crop data in general means that the information in these tables must be used with some caution in making nutritional calculation for specific regions and crop cultivars.

Postharvest Losses

The magnitude of postharvest losses of edible aroids is not well documented; however, the indications are that losses are high. Estimated world postharvest annual losses of edible aroids are about 1 million ton [14]. Under traditional storage systems, losses of about 50% and 95% after 2 and 5 months, respectively, have been reported [15]. Storage losses are higher for taro than tannia [16], presumably due to differences in corm structure, susceptibility to damage during harvesting and handling, and differences in storage potential. Microbial rotting is the primary cause of postharvest losses and reduced storage potential. A wide range of pathological organisms can attack wounds

Table 2.68. Nutritional and chemical composition of edible aroids

	Taro (71 Samples from 3 Countries)	Tannia (37 Samples from 2 Countries)	Giant Taro (37 Samples from 2 Countries)	Giant Swamp Taro (27 Samples from 2 Countries)	Elephant-Foot Yam (7 Samples from one Cultivar)
Moisture (%)	69.1	67.1	70.3	75.4	77.8
Energy kJ·100 g ⁻¹	480	521	449	348	336
Protein (%)	1.12	1.55	2.15	0.51	2.24
Starch (%)	24.5	27.6	21.5	16.8	16.6
Sugar (%)	1.01	0.42	0.96	1.03	0.14
Dietary fibre (%)	1.46	0.99	1.85	2.78	1.45
Fat (%)	0.10	0.11	0.10	0.16	0.06
Ash (%)	0.87	1.04	0.92	0.67	1.36
Minerals (mg·100 g ⁻¹)					
Ca	32	8.5	38	182	97
P	70	53	44	16	67
Mg	115	27	52	21	47
Na	1.8	6.6	30	72	4.1
K	448	530	267	67	622
S	8.5	7.9	12	3.3	12
Fe	0.43	0.40	0.83	0.61	0.51
Cu	0.18	0.19	0.07	0.11	0.18
Zn	3.8	0.52	1.57	2.3	1.05
Mn	0.35	0.17	0.62	0.69	0.31
Al	0.38	0.53	0.36	1.36	0.41
B	0.09	0.09	0.10	0.09	0.17
Vitamins (mg·100 g ⁻¹)					
Vitamin A (ret. + -car./6)	0.007	0.005	0	0.005	0.07
Thiamin	0.032	0.024	0.021	0.025	0.06
Riboflavin	0.025	0.032	0.018	0.019	0.05
Nicotinic acid	0.76	0.80	0.48	0.46	1.2
Pot. Nic. Acid = Trp/60	0.19	0.33	0.46	0.07	—
Total vitamin C (AA + DAA)	15	14	17	16	3.8
Limiting amino acids and score					
First	Lys 66	Lys 57	Lys 64	Lys 70	—
Seconds	Thr 94 Ileu 93	Leu 81	His 91	Leu 97	—
Organic acid anions and calcium oxalate (mg·100 g ⁻¹)					
Total oxalate (Ox)	65	42	42	288	18
Soluble oxalate	35	44	17	45	—

(cont.)

Table 2.68. (Continued)

	Taro (71 Samples from 3 Countries)	Tannia (37 Samples from 2 Countries)	Giant Taro (37 Samples from 2 Countries)	Giant Swamp Taro (27 Samples from 2 Countries)	Elephant-Foot Yam (7 Samples from one Cultivar)
Calcium oxalate	43	23	37	399	—
Free calcium	10	0	15	10	—
Malate	107	211	320	106	105
Citrate	102	314	278	86	142
Succinate	168	506	370	295	0
Trypsin inhibitor (TIU)·g ⁻¹	14	0.3	269	2.5	0.56
Chymotrypsin inhibitor (CIU)·g ⁻¹	0	0	57	0	—

Source: [9].

Table 2.69. Highlights of nutritional and chemical composition of edible aroids

Nutritional and Chemical Composition	
Taro (<i>Colocasia esculenta</i>)	Middle-range energy, protein, and vitamins; high K, Zn; low Na; medium trypsin inhibitor; some cultivars acrid
Tannia (<i>Xanthosoma</i> spp.)	Like taro, but high in nicotinic acid, lowest in free Ca (zero), and low in trypsin inhibitor; some cultivars acrid
Giant taro (<i>Alocasia</i> spp.)	Middle-range energy, highest protein; lowest β -carotene (zero), thiamine, and riboflavin; high Fe and Mn, low K and Cu, very large amount of trypsin/chymotrypsin inhibitor; acrid
Giant swamp taro (<i>Cyrtosperma chamissonis</i>)	Low energy and protein, high dietary fiber, low vitamins; high Na, Zn, and Mn, very low K; large amount of total oxalate and calcium oxalate; some acidity
Elephant-foot yam (<i>Amorphophallus campanulatus</i>)	Low energy, highest protein; high total Ca, calcium oxalate, total oxalate, K, Mg, P, Zn, and Mn; some acidity

Source: [9].

that occur during and after harvest, thereby causing decay and subsequent rots [16–23]. Rot-causing organisms are mostly soil-borne and are found on the surface of corms and cormels at harvest.

2.6.2 Maturity and Harvesting

The condition of the leaves is a good maturity index. Edible aroids are mature for harvesting when the leaves begin to turn yellow and start to wither. Taro generally matures in 240 to 300 days from planting, although the eddo type matures in 180 to 210 days. The corms are lifted by hand and the main tuber often is harvested with the smaller corms left to develop later. Yields are variable but for taro may range from 4 to 6 ton·ha⁻¹ and up to 15 ton·ha⁻¹ has been recorded [13, 24]. Mature taro produces a large edible main corm and a few lateral cormels, about 4 to 10 in number. Tannia is mature in 240 to 420 days after planting, with small cormels 15 to 22 cm in length attached to large corms. These

should be harvested before they produce new shoots. The corms are lifted by hand, and mature cormels may be harvested continuously for 500 days or more, leaving the main corm in the ground. Tannia yields about 6 to 12 ton·ha⁻¹ of corms, but yields of 12 to 20 ton·ha⁻¹ often are obtained.

2.6.3 Postharvest Handling and Curing

Handling

Harvested corms usually are carried in baskets, jute bags, or carts from the farms to storage room or directly to the market for sale to the consumer [1]. Some harvested corms are consumed by the farmers directly or put in storage for later use (Fig. 2.66). Corms are susceptible to mechanical injury during harvesting and postharvest handling, and it has been reported that mechanical damage is the major reason why corms fail to meet consumer and storage standards [1]. Extra care should be taken to avoid damage to the corms during postharvest handling, because the presence of damage may lead to rapid deterioration during subsequent handling and storage. Impact studies have shown that the percentage of corms damaged by dropping does not change very much with drop height (Fig. 2.67), but the severity of damage increases significantly with the drop height (Fig. 2.68).

For the fresh market, taros normally are washed and the roots and fibers discarded. They are graded and packed in crates for transportation. Crates are preferred because they are firm and reduce the incidence of mechanical damage to corms. Corms destined for storage are cleaned but not washed and also may be cured to enhance repair of any physical injury present.

Cleaning the edible aroids to meet strict export quarantine requirements is an essential part of the postharvest handling system. Currently, New Zealand regulation stipulates

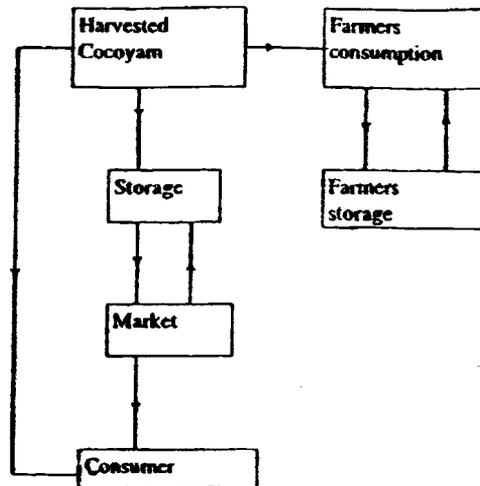


Figure 2.66. Postharvest handling system for corms. (Redrawn from [25])

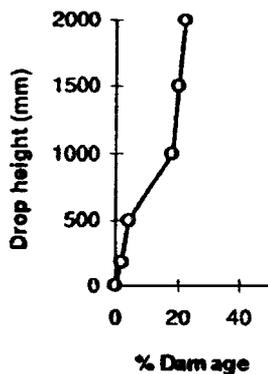


Figure 2.67. Drop height against percent damage of corms.

(Redrawn from [25])

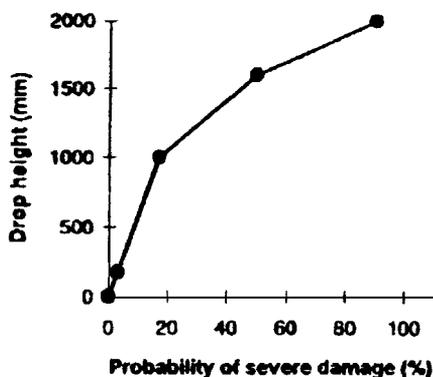


Figure 2.68. Probability of severe damage of corms at different drop heights.

(Redrawn from [25])

no more than 25 g of soil per 600 units (or corms). Taro destined for export is cleaned by hand by scraping or washing in water at the packhouse. Hand cleaning is labor-intensive and takes considerable time and work quality is difficult to control. Although experimental washing of taro corms grown in paddy conditions has been reported, no mechanized cleaning equipment is yet available [26]. Based on an assessment of several crop-cleaning machines in Samoa in terms of time taken to clean to export-crop standard, uniformity of cleaning, damage to corms, complexity of the machine, and cost, it has been recommended that the carrot-barrel washer with some manual finishing could be used for cleaning taro corms to meet export standards [26]. The cost of this machine was about US\$5000 in 1995.

Curing of Corms

Several wounds are made on tannia corm when the cormels (usually 4 to 10 in number) are removed, and one wound inevitably is made on taro cormels when they are cut off from the parent corm. During trimming to remove the residual planting material from the base of the corms and the petiole of leaf base, additional wounds also are made that have poor healing properties [27]. Because wounding of corms is necessary during harvesting and trimming, it is important that the crop is cured before long-term storage to in order to promote a rapid wound-repair process, thereby slowing down the rates of physiological and pathological deterioration.

Traditionally, curing usually is accomplished by placing corms in the sun until the wounded surface dries out. Corms also can be cured in naturally ventilated barns or other storage structures. Curing is less effective if damage to corms is extensive. Fungicide treatment may be necessary if base trimming is practiced.

In-depth studies on the effects of curing on aroids are scanty. Curing can be achieved at elevated temperatures in a high-humidity environment, but the application of agrochemical sprout-suppressants has been suggested to cause an inhibitory effect on wound healing and periderm formation [17, 28, 29].

Curing corms at 35°C and 95% relative humidity for 5 days reduces the rate of sprouting and weight loss in tannia [12, 25], and temperatures below 20°C have been reported to cause very slow wound healing of dasheen cormels [27]. It was recommended that brief storage of corms under tropical ambient conditions (24 or 30°C with 85% humidity) promoted curing in taro and tannia corms [30, 31]. Other studies have reported that the best conditions for wound healing were 34 to 36°C with 95% to 100% relative humidity [32]. However, under these conditions wound healing occurred more readily at the top of corms than at the base and sometimes failed to occur at the base. If corms had severe bruising, periderm develops sporadically.

2.6.4 Storage of Fresh Corms

There is considerable variation in the storage behavior of the different edible aroids. Taros are more difficult to store than tannia [17, 31]. Storage of fresh corms is important for distant marketing, to free farm land for new cropping, and to ensure the availability of seed cormels in the next planting season. Edible aroids have a short period of shelf life, however, and this creates specific problems with the supply of new planting materials. In particular, storage at ambient temperatures is considered impossible due to a very high incidence of fungal decay. Under high storage temperatures (25°C and above) and humidities (85% and above), more sprouting and decay occurs with taro than with tannia cormels [31]. However, less sprouting and decay occurred with taro at high temperature and low humidity than at high temperature and high humidity, but weight loss was higher. Under tropical ambient conditions, tannia cultivars were stored successfully for about 5 to 6 weeks, but up to 60% decay occurred in taro corms.

Traditional Low-cost Structures

Aroids are stored in a variety of traditional low-cost structures such as shade, huts, and underground pits. Sometimes the corms are placed in boxes before loading into the

building. Corms also may be stored in heaps in the shade or covered with straw or plantain leaves. In parts of southern China, it is common practice to pile the corms in heaps and cover them with soil or seal them in leaf-lined pits in the ground [33]. In parts of the Philippines, corms are stored on wooden platforms with the corms arranged in irregular rows and covered with dry grass and finally with soil. As practiced in some parts of the South Pacific, corms may be harvested with about 30 cm of their basal petioles attached, tied into bundles, and stored suspended in the shade. In pit storage, corms are placed inside pits and covered with leaves and soil [34]. Storage in leaf-lined soil pits also is practiced. The pits or trenches usually are dug in well-drained soil in shaded areas. In some parts of Nigeria, the trenches then are covered with dry grass and finally soil. These traditional storage conditions reduce moisture loss and promote the curing of wounds. The storage life of taro corms has been extended for up to 4 weeks with no effect on the storage of tannia [21, 27, 34]. Under these conditions, the incidence of fungal infection is reduced and the corms remain physiologically active, leading to production of roots and shoot.

Studies carried out in Cameroon showed that traditional storage pits in a confined environment gave more satisfactory results than storage on trays in well-ventilated huts [7]. After several weeks of storage, there was no difference in taste or texture between stored and fresh corms. After 4 weeks, however, 10% to 20% of the corms was destroyed by bacterial infection. Storage losses can be reduced by minimizing the occurrence of mechanical damage and leaving the corms untrimmed [4]. Taro can be stored in shaded pits for about 4 months without significant losses in quality and quantity, and satisfactory storage has been achieved for up to 3 months under a variety of tropical conditions. In general, tannia keeps better in traditional pit storage than in a ventilated room or barn [13]. Mature tannia corms do not deteriorate if left in the ground, and it is also common practice to harvest corms for immediate utilization as required.

Modification of traditional storage structures to achieve improved environmental control also can improve the storage life of corms and reduce incidence of decay. For instance, a comparison of corms (with roots and petiole intact) stored in a modified clamp (27–28.4°C, 90%–98.8% relative humidity) or in a hut (29.8–32°C, 58.8% humidity) showed that the percentage of decay was less in clamp storage than in hut storage.

Although most traditional methods of storage have been practiced since time immemorial, they are suited mainly for short-term storage and have limited success with long-term storage, which is a prerequisite for modern-day postharvest handling and marketing. Existing results are largely variable, and in many instances the corms decay and become unfit for human consumption after a short period. Different levels of corm wastage and losses have been reported for different lengths of storage and for the different types of edible aroids (Table 2.70).

It has been shown that taro and tannia can be stored at tropical ambient conditions (24–29°C with 86%–98% relative humidity) for at least 2 weeks without significant changes in nutritional values such as crude protein content and total amino acids [31]. However, there is a significant reduction in starch content and an increase in total sugar content. During this period, also, sucrose was the most abundant sugar and maltose was consistently the least abundant in both fresh and stored corms.

Table 2.70. Storage losses of corms under traditional storage methods in ambient conditions

Type of Aroid	Length of Storage	Degree of Losses
Taro	5–10 d	Became unfit for human consumption
Taro	1–2 wk	Became unfit for human consumption
Taro	2 wk	Decayed rapidly
Taro	6 wk	28% fresh-weight loss and 53% decay
Taro	2 mo	50% loss
Taro	3 mo	More than 30% wastage
Taro	5 mo	95% loss
Tannia	2 wk	5% decay
Tannia	6 wk	35% fresh-weight loss and 40% decay

Compiled from [15, 17, 21, 23, 35].

Table 2.71. Recommended storage conditions for tannia

Temperature (°C)	Relative Humidity (%)	Length of Storage
7	80	17.1–18.6 wk
7.2	80	18 wk
7–10	80	16–20 wk
15	85	5–6 wk

Compiled from [13, 31, 37, 38].

Ventilated Storage

During storage in well-ventilated stores (about 26°C and 76% humidity), tannia corms had 1% weight loss per week, but sprouting occurred after 6 weeks. The corms still were edible after 9 weeks, storage [36]. Other studies have shown that tannia corms may be stored in well-ventilated conditions for up to 6 months [13, 21], although loss of eating quality was observed after 8 weeks. Several factors including corm maturity, environmental condition, agroclimatology, extent of physical injury, and preharvest factors contribute to the variable storage results. Studies carried out in the Philippines showed that ventilated storage of corms in the dark at 24°C resulted in 30% decay after 1 to 3 weeks [7].

Refrigerated Storage

Corm storage life is improved using low-temperature refrigerated storage (Tables 2.71 and 2.72). However, refrigerated-storage techniques have higher costs compared with traditional and ventilated-storage methods. They require capital investment in equipment, packaging, relevant skilled technical labor, and a power supply.

Selection of any storage technique must be guided by consideration of a crop's economic value, its intended use, and the appropriateness of the technology to local conditions.

At low temperature (15°C) and high humidity (85%), both taro and tannia successfully have been stored for 5 to 6 weeks [31]. Storage life generally is improved at conditions of lower temperature and high humidity. If the storage environment can be maintained

Table 2.72. Recommended storage conditions for taro

Temperature (°C)	Relative Humidity (%)	Length of Storage
4.4	—	3.5 mo
6.1–7.2	80	—
7.2	70–80	90 d ^a
7.2	85–90	120–150 d ^b
7–10	85–90	4–5 mo
10	—	Up to 180 d ^c
10	—	6 mo
11.1–12.8	85–90	21 wk
11–13	85–90	5 mo
12	90	5 mo
13.3	85–90	42–120 d
20	60	2–4 wk

Compiled from [7, 13, 36, 38–43].

^a Malanga type.

^b Taro type.

^c Dasheen type.

at 11 to 13°C and 85% to 90% relative humidity, the length of storage of taro can be extended to about 150 days. For tannia, storage at 7°C and 80% humidity has been found to maintain corms in good condition and good eating quality for about 120 to 130 days [13]. Taro packed in soil in brick containers or in pits stored for up to 5 months in China at ambient temperature of 8 to 15°C or lower [4]. Storage periods of 6 to 7 months also have been recorded under similar conditions [33]. International sea- and air-freight shipping of taro from the South Pacific in refrigerated containers and chambers and subsequent storage at 3 to 5°C in market stores is now practiced commonly. The corms remain in good condition for up to 6 weeks, but once they are exposed to ambient conditions they deteriorate rapidly after 24 hours [44]. Tannia export shipments at 13 to 14°C from Puerto Rico to the United States generally are in poor condition on arrival after the 9-day journey. After subsequent storage at 15°C and 65% relative humidity for 30 days, the corms had decayed.

Other Storage Techniques

Aroids also have been stored in plastic bags alone or in combination with traditional storage structures. The conditions created inside the bag reduce moisture loss and facilitate the curing of wounds. Packing taro corms in plastic bags and closely tying the open end with rubber bands reduces the decay severity and percentage weight loss [45]. For commercial handling purposes, packing in polyethylene bags often follows the selection of good-quality corms, fungicide application and draining, and air drying. It has been reported that the storage life of corms in such bags was 26 to 40 days longer than the life of those packed in cartons [7]. Taros stored in polyethylene bags showed a 6% loss in fresh weight and 50% decay; tannia suffered a 9% weight loss and 30% decay [17]. In comparison with traditional storage in trenches or pits, corms kept in polyethylene bags survived well for up to 30 days without appreciable changes in taste and

texture. Dipping corms in 1% NaCl before storage in polythene bags provided additional protection against fungal infection [35], and the best storage results were obtained when the petioles and corm apex were left intact. Ash may be added as a fungicide.

Storage media such as coir dust and hull ash have been reported to increase storage life and reduce the severity of decay of corms. In trials with *Colocasia* (dasheen type), placing corms in a medium of rice-hull ash extended the usual storage life of corms by 14 days [46]. The following procedure was followed: Corms with petioles and about 5 cm of leaf stalk were packed in boxes made of marine plywood (46 × 61 × 31 cm), and rice-hull ash (40%–45% moisture) was spread evenly at the bottom of the box at a thickness of about 5 cm. A layer of corms was placed on the ash and covered with another layer of the same medium about 3 cm thick. This arrangement allowed 10 corms in a box. Results showed that after 30 days, storage, corms stored in moist rice-hull ash had the least weight loss (8.5%) and severity of decay (<20%) compared with corms stored without any medium, which had decay severity 80% or greater. In addition, corms stored without medium also were the first to show severe decay.

The presence of roots and petioles affects the storage potential of edible aroids. In a study of three groups of taro corms (without petiole and growing point; with a growing point and 15 cm petiole; and with a growing point and 30 cm petiole), packed in plastic boxes (46 × 30 × 15 cm) and stored inside a building with adequate ventilation and lighting (20.7–24.3°C) over a period of 5 weeks, the corms incurred weight losses of 16.1%, 22.0%, and 27.4%, respectively [47].

In another study [48] with four categories of taro corms (group I with roots and petioles, group II with petiole and roots removed, group III with roots and petiole removed, and group IV with roots and petiole intact) stored under ambient conditions (27–32°C, 65%–85% relative humidity) over a period of 2 weeks group I corms showed a smaller weight loss and more severe decay (20% of total corm area); groups II and IV showed more weight loss but less decay. Group IV also had less decay and more weight loss than group I when corms were stored in a modified clamp or in a hut. The biochemical pathways or physiological mechanisms for the reduction of decay in corms stored with petioles and roots is not yet known; however, the greater weight loss was attributed to the increased surface area for moisture transport due to the presence of petiole and roots, in addition to the high sap and water content of the petiole.

Tannia corms can be stored satisfactorily in damp coir media with significant reductions in weight loss and decay incidence. During a 6-week storage trial in which edible aroids were put in boxes containing coir dust and stored under ambient conditions (27–32°C), taro corms showed a 28% weight loss and 50% decay, while weight loss and decay were 30% and 25%, respectively [17]. If corms were stored in boxes containing moist coir, taro showed a 21% weight loss and 50% decay, while weight loss and decay were only 7% and 5%, respectively. For best results, it important to ensure that the coir is damp and not wet, as the latter exacerbates decay of corms.

2.6.5 Control of Storage Diseases and Disorders

Rot and decay of stored corms is a problem with edible aroids and can be caused by representatives of all the major taxonomic groups [4]. Fungicide application is often

Table 2.73. Effectiveness of fungicides commonly used to control postharvest decay of edible aroids

Fungicide	Effectiveness
Benomyl	Effective where <i>Botryodiplodia theobromae</i> is the predominant decay organism; ineffective against <i>Phycomycetous fungi</i> ; recommended in countries where <i>Phytophthora colocasiae</i> and <i>Pythium splendens</i> cause major storage losses
Copper oxychloride	Controls corn rots caused by <i>P. colocasiae</i>
Captafol, mancozeb	Only delay <i>B. theobromae</i> rots by ~10 d
Sodium hypochlorite	Effective against all common storage decay fungi in the Pacific except <i>Sclerotium rolfsii</i>

Source: [4].

necessary, and to be effective the fungicide must have a large spectrum of activity to cover the broad range of decay-causing microbial organisms. Tannia suffers from far fewer postharvest problems than does taro, and fungicide treatment often is recommended [31]. Microbial rotting and decay in stored edible aroids has been delayed with varying degrees of success by prestorage application of fungicides as dips and dusts. A summary of major fungicides applied and their effectiveness is presented in Table 2.73. It should be noted that sodium hypochlorite is cheaper and safer to handle than other fungicides and leaves no residue on the corms [34, 44]. To be effective, the fungicide must be applied within 24 hours of harvest [49]. In addition to fungicide treatment, waxing and chlorine dips also reduce storage losses of tannia [50]. As in all cases, the use of fungicides and indeed all agrochemicals must be checked with the appropriate local agrochemical authority or agency, as there are many regulations limiting the use of certain materials.

Dormancy is important in edible aroids because it determines the storage life of corms. Storage is no longer possible once sprouting occurs. The mechanisms and physiological basis of dormancy in aroids have not been well studied. Although it is believed that corms generally exhibit short dormancy, and the existence of dormancy in tannia cormels has been suggested [51, 52], no experimental evidence is available to support this.

Edible aroids are susceptible to chilling injury with low-temperature storage, although the phenomenon has not been investigated extensively. Internal browning due to chilling injury after storage of taro at 4°C for 10 days has been reported [53].

2.6.6 Agroprocessing and Utilization

The food requirement of the rapidly increasing population in tropical developing countries exerts tremendous pressure on the agricultural sectors and food supplies in these regions. The short postharvest shelf life of edible aroids, especially taro, even under refrigerated storage makes it essential that practical and economical methods be developed and used to derive maximum utilization and popularization of these underutilized tropical root crops. In addition to the conventional uses as vegetables (boiled, fried, or baked), the corms and leaves of edible aroids also can be processed into secondary food products as well as raw materials for livestock and other industries. It should be noted that the corms of taro and tannia contain raphid and small quantities of cyanide

and therefore should not be fed to humans or livestock without cooking. Raphids are minute bundles of crystals of calcium oxalate (0.1%–0.4% of fresh weight of taro), which accounts for the irritating effect of the raw corm.

Processed Food

The readily digestible small starch grains of taro (1–4 μm) compared with the large grains of tannia (17–20 μm) makes taro suitable for several food products especially as food for potentially allergic infants, and persons with gastrointestinal disorders [2]. Among the root crops, taro is perhaps most widely prepared or processed into more consumable forms. These include poi (fresh or fermented paste, canned, and canned-acidified), flour, cereal base, beverage powders, chips, sun-dried slices, grits, and drum-dried flakes [54, 55].

Cocoyam flour can be manufactured in several ways, but the key operations include peeling fresh or precooked corms and cormels, drying, and grinding into flour. In commercial practice, the flour is made by peeling the corms and cormels, slicing them, and washing them thoroughly with water to remove adhering mucilage. After soaking in water overnight, the slices are washed and immersed in 0.25% sulphurous acid for 3 hours. Finally, the slices are blanched in boiling water for 4 to 5 minutes, dried thoroughly at 57 to 60°C, and then milled into flour. The details and comparison of alternative processes for manufacturing cocoyam flour are well documented [54], including those developed and practiced in Hawaii, India, Samoa, and Nigeria.

The corms and cormels of cocoyams can be boiled and pounded into a paste like pounded yam in parts of West Africa. In southeastern Nigeria in particular, boiled cocoyams also can be mixed with boiled yam or gari (a type of cassava flour) and pounded into a paste. The paste usually is made into balls and swallowed after dipping in soup or stew.

Taro also can be processed into poi, which is a purplish-gray paste. Poi is considered an excellent food and is popular in Hawaii and the South Pacific. It is sold commercially in plastic bags, jars, or cans in Hawaii. Poi is prepared as follows: First, the corms and cormels are pressure-cooked, washed, peeled, and mashed into a semifluid consistency; the product then is passed through a series of strainers, the final strainer having a 0.5-mm diameter grade; and finally, the product is bagged and sold as fresh drink or stored in room temperature to ferment through the action of *Lactobacillus* spp. bacteria. Following the fermentation, the product becomes more acidic (pH declines from about 5.7 to 3.9). In some areas, coconut products may be added to the fermented poi before consumption.

Canned fresh (“ready-to-eat”) poi is the unfermented product less than 4 hours old containing 18% total solids or more. For a standard 566-g can, the thermal process requires about 100 minutes of cooking time at 116°C [56]. On the other hand, canned-acidified poi is the unfermented product less than 4 hours old to which 1% w/w commercial-grade lactic acid (50% lactic acid) has been added. It usually contains 18% or more total solids, with a shelf life comparable to other canned foods [56]. In trials with gamma-radiation, a minimum of 7 kGy was required to increase the shelf life of poi to 7 to 10 days [57]. High-quality dehydrated poi made by freeze-drying has been reported; however, the process was considered expensive.

The edible aroids, and in particular taro, can be made into about a dozen different food products. An extensive review of the experimental and commercial processes for these products can be found in ref. [54], and readers interested in these details are advised to consult this reference. In summary, these reports demonstrate that stable intermediate products such as flour and dried slices can be prepared and further extruded into convenient, ready-to-use, stable forms such as taro rice, noodles, and macaroni.

Animal Feedstuff

In many parts of the tropics and subtropics where cocoyam and other root crops are grown as staple foods, development of the livestock industries still is hampered by the lack of or inadequate production of feeds. Often, imported feeds are too expensive for farmers in these subsistence environments. The use of cocoyam by-products including leaves potentially could maximize animal production at minimum expense to assist in meeting the food requirements in these areas. Besides the benefit of producing animal feed and therefore either a new source of income or the ability to feed more domestic livestock, removal of the leaves would improve field sanitation [58] and reduce the subsequent land preparation required.

It has been noted that root crops in general, and taro in particular, would make an excellent source of animal feed [59]. Silage made from the entire crop was suggested specifically. Indeed, taro corms, cormels, and leaves are used to a limited extent as animal feed. This limited use is attributed to the acidity problem that renders the leaves, petioles, and corms unacceptable for use without costly, high-energy preparation [60]. All parts of the plant contain acrid principles that are irritating to the mouth and esophagus; these can be removed by cooking or fermentation.

The potential of cocoyams as an animal feed is too great to be ignored, considering the high yield of petioles, top, and leaves. Based on an average of 2 kg of taro tops per plant per 31 weeks and a spacing of 80 × 80 cm, a yield of 52.5 metric ton per hectare per year has been estimated [61]. Some aroids such as giant taro can yield up to 167.8 metric ton of leaves and stems per hectare per year. Optimum fertilizer application raised the yield to 226.8 metric ton per hectare per year, the equivalent of 27.2 metric ton dry matter with 34% crude protein and 17% carbohydrates [62, 63]. Experimental trials indicate that up to 7 ton of taro leaves and petioles per hectare can be achieved in a 3-month period [64]. Yields of 9 to 14 and 16 to 25 ton·ha⁻¹·y⁻¹ fresh weight of tops have been reported for Lehua Maoli and Bun-Long aroids, respectively [61].

Considering the high moisture content of the plant tops (up to 88%) in addition to the acidity problem, there is clearly the need for some level of processing for storage and neutralization of the acidity if root and tuber crops are to be used for animal feed. Field-drying alone cannot adequately meet this requirement for leaves, tops, and petioles, considering their high moisture content and the environmental conditions under which the crop is grown. The silage process therefore has been recommended, and the goal is to have the material ferment quickly and reach a state of equilibrium [65]. A good silage therefore should have less than 75% moisture, a pH of 4.5 or below, a low ammoniac nitrogen level; little or no butyric acid, and a lactic-acid content of 3% to 13% on a dry-matter basis [65–67].

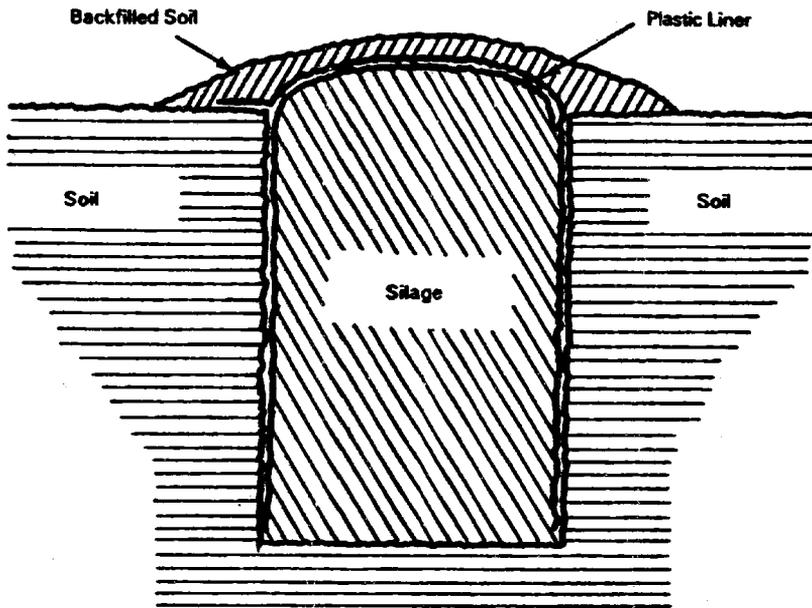


Figure 2.69. Typical cross-sectional view of a trench silo for ensiling taro. (Source: [68])

The silage process is well documented in general agriculture literature. It depends primarily on lactobacilli acting in anaerobic conditions to lower the pH of the forage through production of lactic and other organic acids to preserve the material. The availability of carbohydrates in the forage as an energy source for the lactobacilli is critical. For materials destined for ensiling, proper harvesting and packing techniques must be used to ensure that air is excluded from the trench. This also prevents the production of unwanted products such as butyric acid. Successful ensilage is measured in terms of the efficiency of preservation and the usefulness of the end products for animal feed. The lactic acid is the primary constituent that preserves the silage and also has a positive correlation with animal intakes due to increased palatability. However, the primary factor affecting the performance of animal feed on silage is the feeding value of the crop at the onset of ensiling [68].

Experimental trench silos have been constructed and used successfully to ensile the leaf, petiole, and whole parts of taro (Fig. 2.69). Based on test results, it was found that the acrid factor or factors in taro were either neutralized or destroyed, whereas the raw, unensiled material was quite acrid and caused irritation to workers handling the material. In addition to these results, other studies on the feeding value of taro silage have shown that the fermentation characteristics are comparable with other silage, and that taro silage could meet much of the feed needs for brood sows with no reproductive problems and good litter performance [61].

The problem posed by the high moisture content of taro silage (90%–92% water) as an animal feed can be minimized by ensiling taro tops along with other feedstuffs

Table 2.74. Feeds satisfactorily ensiled with taro tops

Energy Feeds	Dry Roughness and Grasses	Agricultural By-products
Rolled barley	Rice straw	Rice bran
Rolled corn	Guinea grass hay	Chopped banana plant
Pineapple bran	Pangola grass	Whole-plant sugarcane
Molasses	Paragrass	Seedcane tops; cane trash

Source: [61].

(Table 2.74). This ensiling process also allows the preservation of taro forage without the use of energy for drying.

In many tropical developing countries, edible aroids and other indigenous nonconventional feedstuffs can help to lower feed-energy costs and save some quantity of cereals for human food. Results of chicken-feeding trials have demonstrated that root crops such as taro can serve as base feeds in replacement of cereal (corn) with better cost and performance [69–72]. Analysis of the economic costs of using taro in broiler rations in the Philippines showed that the use of taro meals at 12.5% yielded a better profit and had a better rate of return on investment than the control with corn as the base feed, and it was concluded that taro meal can replace corn in terms of profit for broilers at 49 days [73]. A minimum of 20 chicks were used for each treatment. Typical composition of different rations and the performance evaluation on broiler chicks are shown in Tables 2.75 and 2.76.

Table 2.75. Composition of different taro-based rations and a control used in feedstuff evaluation

Feedstuff	Rations				
	A	B	C	D	E
Taro (%)	0	12.5	25.0	37.5	50.0
Corn (yellow) (%)	50.0	37.5	25.5	12.5	0
Rice bran (%)	5.0	5.0	5.0	5.0	5.0
Copra meal (%)	12.0	9.8	7.7	5.6	3.5
Soybean-oil meal (%)	18.0	20.0	22.0	21.0	26.0
Fish meal (%)	10.0	10.0	10.5	10.0	10.0
Ipil-ipil leaf meal (%)	3.0	3.0	3.0	3.0	3.0
Bone meal (%)	1.0	1.0	1.0	1.0	1.0
Vegetable oil (%)	0	0.2	0.3	0.4	0.5
Salt (%)	0.5	0.5	0.5	0.5	0.5
Vitamin-mineral premix	0.5	0.5	0.5	0.5	0.5
Calculated analysis					
Protein (%)	21.79	21.79	21.84	21.84	21.86
Fat (%)	4.33	4.17	3.92	3.66	3.37
Fiber (%)	4.96	4.91	4.86	4.82	4.78
Energy (Kcal·kg ⁻¹)	2993.27	3025.23	3052.04	3078.85	3105.66
Protein-energy ratio	1:137.37	1:138.34	1:139.75	1:140.97	1:142.07

Source: [73].

Table 2.76. Cost and feed performance analysis on broiler chicks fed on taro meal

Taro Meal	Treatment				
	0%	12.5%	25%	37.5%	50%
Cost of production (P)	25.85 a	24.24 abc	25.44 ab	25.04 abc	22.04 d
Profit (P)	4.36 b	6.16 a	0.84 c	-3.72 d	-3.77 e
Return on investment (P)	16.89 b	25.41 a	3.21 c	-14.87 d	-17.11 e
Feed cost per kg live weight (P)	15.26 d	14.99 d	17.77 c	24.95 b	30.97 a
Initial weight (kg)	46.9	46.9	46.9	46.9	46.9
Weight gain (kg)	1324.8 ab	1335.1 a	1148.6 c	922.1 d	798.47 d
Feed consumption (kg)	3634 cd	3638.2 cd	3770.9 c	4342.2 b	4678.3 a
Feed conversion efficiency	2.05 cd	2.02 cd	2.35 c	3.24 b	4.12 a

Adapted from [73].

Note: Any two means having a common letter in a row are not significantly different at 5% using DMRT.
P, Phillipine pesos.

Industrial Raw Materials

Industrial use of edible aroids is very limited, although the starch (an important industrial raw material) content of taro, for instance, accounts for nearly 78% of the carbohydrate fraction (Table 2.77). The small size of the taro starch grains (1–4 μm) makes them readily digestible as a food material but unsuitable as a source of industrial starch. Furthermore, although the protein content of taro corms (1.4% to 3.0% on fresh-weight basis and about 7% on a dry-weight basis) is slightly higher than that of other major root and crops, and they are also rich in essential amino acids, they are rather low in histidine, lysine, isoleucine, tryptophan, and methionine [2].

Despite the considerable efforts made and some success achieved in promoting the growing and utilization of aroids as a food source in many tropical developing countries, economic considerations such as high labor demand and special agroclimatology requirements for crop growth so far have hampered the exploitation of edible aroids

Table 2.77. Fractional analysis of carbohydrate content of taro corm

Component	%
Starch	77.9
Pentosans	2.6
Crude protein	1.4
Dextrin	0.5
Reducing sugars	0.5
Sucrose	0.1
Amylose	17–28

Sources: [74, 75].

Table 2.78. Characteristics of taro starch, cereal starches, and potato starch

	Particle Size (μm)	Pasting or Gelation Temperature ($^{\circ}\text{C}$)
Taro		
Akalomama	6	64
Bun-Long	5	71
Antiquorum (cv Martin)	3.5	68
Wheat	~ 15	54
Rice	5	64
Potato	50	60

Source: [78].

as export crops and sources of industrial raw materials. Starch derived from the edible aroids, however, has the potential to augment the high demand of world cereal crops and other starch-yielding crops that are especially capable of growing in tropical and water-logged terrain.

The special quality attributes of aroid starch that are relevant to industrial applications include particle size, pasting temperature, and amylose content. The particle size of starches of aroids sets them apart conspicuously from more familiar commercial starches. Comparison of the results of microscopy [76, 77] and laser-light scattering [78] studies shows that several taro varieties have particle sizes 1 to 6.5 μm mean diameter, compared with rice starch at about 5 μm , which is the finest of the commonly available starches. Thus, taro starch literally takes over where the commercial starches finish. On the other hand, the starch of tannia has relatively large grains with average diameter of 17 to 20 μm . Edible aroids, therefore, cover a unique wide range of particle sizes.

In addition to particle size, pasting or gelation temperature of starch also is important during processing and industrial applications. Data available indicates that aroids have high gelation temperatures compared with traditional starch sources (Table 2.78). These data indicate that edible aroids and taro in particular could provide a unique combination of small particles with high gelation temperatures.

In combination with small particle size, taro varieties can offer a choice of high or low amylose content, as indicated by iodine affinity (Table 2.79). Assessment of amylose content by iodine affinity is the most widely reported measurement for quantifying the internal structure of starch grains, and this generally is determined by potentiometric titration [81]. The amylose of taro starch has 490 glucose units per molecule; the amylopectin has 22 glucose units per molecule.

Consideration of these properties of aroids (taro in particular) and a review of general starch-application technology highlights specific areas in which the properties of aroids starch can be applied in commercial industries. These areas include cosmetics, syrups, gums, modified-atmosphere packaging film, fillers/modifiers for plastics, and renewable energy. These industrial applications have been reviewed extensively [54], and only a summary of the major potential uses are presented here.

Table 2.79. Iodine affinities of taro starch and other crop starches

	Particle Size (μm)	Iodine Affinity (%)
Taro		
Uramata	1.5–4.0	2.5
Globulifera	2.0–5.5	3.7
<i>Amaranthus pariculatus</i>	3.2	0
Maize	15	3.1

Sources: [79, 80].

Syrup Production

World production and demand for industrial syrup has increased considerably in the past few decades and is predicted to continue to do so in the future. Like other vegetable starches, aroid starches could be processed into high fructose-enriched syrup, which is a liquid sugar (sweetener) made from starch. The nutritional value of high fructose-enriched syrup is similar to that of sucrose, and it is a very desirable, inexpensive sweetener. Facilities can be built in areas in which starch is available and inexpensive. Local uses include canning, jams, jellies, and soft drinks. Production of high fructose-enriched syrup from aroids involves four stages: production of starch from corms, liquefaction of starch with alpha-amylase, saccharification with glucoamylase, and isomerization with glucose isomerase.

Gum Production

Aroids contain a gum-like substance that swells in water and becomes hydrated [82, 83]. This gum has potential usefulness as an emulsifying, thickening, and smoothing agent for creams, suspensions, and other colloidal food preparations. Extraction of the gum also would alter the properties of aroid products and reduce their stickiness and viscosity.

Renewable Energy Source

There is considerable global concern about the depletion of nonrenewable energy sources and the effects of fossil fuel on environmental degradation. In most developing countries, low energy input often is a major limitation to increasing agricultural productivity and overall rural development. Many countries could reduce their dependence on imported oil appreciably by replacing part of their petroleum consumption with alcohol produced from sugar- or starch-containing crops. Given a favorable domestic economy, the edible aroids would serve well as a feed material for energy generation. The alcohol yield of taro is lower than that of cassava and cereal crops but higher than that of sugarcane and sweet corn (Table 2.80). The accepted starch-to-alcohol conversion ratio is about 1.67 kg of starch to 1 L of alcohol, and in the United States alcohol production costs from taro were considered similar to cassava or sugarcane and estimated to be \$0.15 per liter in 1978 [84–86], compared with ethanol production from corn at \$0.11 per liter.

Table 2.80. Alcohol yield and cropping cycle for selected crops

Crop	Alcohol Yield (L·ton ⁻¹)	Cropping Cycle (mo)
Taro	142	9–15
Sweet potato	142	5
Sugarcane	67	10–22
Sweet sorghum	76.7	4
Cassava	180	12
Corn	385	3.5
Spring wheat	368	4
Grain sorghum	389	3.5

Modified from [78].

Modification of Plastics

Starch can make up to 40% of plastics compounds based on such polymers as polystyrene, polyethylene, and polyvinyl chloride, and the addition of modest amounts of starch does not materially affect the original physical properties of the plastics [78]. Taro starch is biodegradable, and if it is used in appropriate formulation in the production of plastics, it accelerates the biodegradability of the parent polymer [87]. In addition, the starch does not exclude the possibility of recycling the majority of plastics composition. With the increasing global demand and utilization of processed food and raw materials in general, biodegradability has become an increasingly important requirement in agricultural and industrial waste management.

The small size of taro starch granules (approximately one tenth the size of maize starch granules) makes them superior to other starches for the production of biodegradable plastics [76]. The importance of particle size of a filler or modifier in plastics is attributed to its influence on the processing properties and its influence as the subphase in the resulting solid composite. The mechanism for the biodegradability of aroid starch is as follows: Starch is progressively removed from the plastic through selective degradation by bacteria for fungi, and the removal of the starch increases the surface area of the plastic and accelerates the rate of degradation [88]. The advantages of using taro starch in plastic production are summarized in Table 2.81.

Modified-Atmosphere Packaging

Modified-atmosphere packaging technology utilizes the permeability characteristics of films and other packaging materials to influence the exchange of O₂ and CO₂ mainly to control the rate of ripening and other physiological activities of fresh food products inside a package. Measurement of the absolute gas permeability of starch-filled polyethylene films showed a significant decrease in permeability with increasing starch content [78]. This effect was attributed to the high degree of crystallinity of the starch filler material, a property shared by mineral fillers. The low fixed-gas permeability of taro starch makes it a potential candidate for developing appropriate modified-atmosphere packaging technologies, especially in the tropical root-crop regions, in which production of root crops is a major part of agricultural production. A taro-based packaging film has been successfully developed but was found expensive compared with low-cost synthetics [90]. The

Table 2.81. Advantages of using taro starch in plastic production compared with other minerals

Taro Starch	Minerals
Density comparable with plastics: 1.49 ton·m ⁻³	High density, ranging from 2.6 ton·m ⁻³ for silica to 4.6 ton·m ⁻³ for barytes
Narrow particle size range; low porosity; very small particle size—can therefore be used in surface coatings or very thin films	Broad particle size range, often with a high fines content; very low porosity, except certain chalks, dolomites and clays
Simple particle geometry approaching spherical and regular, minimum disturbance to melt rheology	Irregular particles, mostly fracture fragments from grinding operations; large surface area
Very low abrasive properties	Often extremely abrasive
Colourless and most transparent, R.1.–1.52, can yield translucent or near-transparent products	Usually colorless but of high refractive index, e.g., calcite—1.66, wollastonite—1.63, talc—1.59; blends with polymers are white and opaque
No significant metallic content; starch itself is an accepted food product	Transition metals may be released; possible interference with antioxidant function; possible toxicity questions
Thermally stable to 250°C	Thermally stable to very high temperatures
Not water-soluble, but hygroscopic. Also hygroscopic in situ	Some minerals retain traces of water tenaciously, but not normally hygroscopic in situ
Low fixed-gas permeability	Very low fixed-gas permeability
Biodegradable formulations possible	Permanent in a biologically active environment

Source: [89].

unique property of certain taro starches deserves further investigation to develop more cost-effective extraction techniques.

References

1. Yamaguchi, M. 1983. *World Vegetables*. Westport, CT: AVI Publishing.
2. Onwueme, I. C., and W. B. Charles. 1994. Tropical root and tuber crops: Production, perspectives and future prospects. FAO Plant Production and Protection Paper 126. Rome: Author.
3. FAO. 1988. *Production Yearbook*. Rome: Author.
4. Cooke, R. D., J. E. Rickard, and A. K. Thompson. 1988. The storage of tropical root and tuber crops: Cassava, yam and edible aroids. *Experimental Agriculture* 24:457–470.
5. FAO. 1983. *FAO Production Yearbook*, vol. 46, FAO Stat. Ser. No. 112. Rome: Author.
6. FAO. 1991. *Production Yearbook*, vol. 44 for 1990. Rome: Author.
7. Kay, D. E. 1987. *Crop and Product Digest no. 2: Root Crops*, 2nd ed. London: Tropical Development and Research Institute.
8. Tindall, H. D. 1986. *Vegetables in the Tropics*, Hong Kong: ELBS.
9. Bradbury, D. H., and W. D. Holloway. 1988. *Chemistry of Tropical Root Crops*. Canberra, Australia: Author.

10. FAO. 1968. *Food Consumption Table for Use in Africa*, Bethesda, MD: FAO and U.S. Department of Health, Education and Welfare.
11. FAO. 1972. *Food Consumption Table for Use in East Asia*. Rome: Author.
12. Platt, B. S. 1962. Table of representative values of food commonly used in tropical countries, Medical Research Council, Spec. Rep. Series No. 302. London: HMSO
13. Tindall, H. D. 1983. *Vegetables in the Tropics*. London: The MacMillan Press.
14. Booth, R. H. 1982. Storage. In *Pest Control in Tropical Root Crops*, PANS Manual No. 4, pp. 37–55 London: Centre for Overseas Pest Research.
15. Praquin, J. Y., and J. C. Miche. 1971. Essai de conservation de taros et macabo au Cameroun. IRAT, Station de Dschang, Report preliminaire 1.
16. Okeke, G. C. 1982. Studies on the etiology and symptomatology of root and storage rot disease of cocoyam in Nigeria. *Beitraege zur tropischem Landwirtschaft und veterinaermedizin* 20:287–293.
17. Passam, H. C. 1982. Experiments on the storage of eddoes and tannia (*Colocasia* and *Xanthosoma* spp.) under tropical ambient conditions. *Tropical Science* 24(2):9–46.
18. Maduwesi, J. N. C., and R. C. I. Onyike. 1981. Fungal rotting of cocoyams in storage in Nigeria. In *Tropical Root Crops: Research Strategies for the 1980s, Proceedings of the 1st Triennial Root Crops Symposium*, ed. E. R. Terry, K. A. Oduro, and F. Caveness, pp. 235–238. ISTRC-Africa Branch, 8–12 September, Ibadan, Nigeria.
19. Nwufo, M. I., and A. O. Fajola. 1981. Storage rot diseases of cocoyam (*Colocasia esculenta*) in South Eastern Nigeria. *J. Root Crops* 7(62):53–59.
20. Ogundana, S. K. 1977. The pathogenicity of the fungi causing rot in the corms of cocoyam (*Xanthosoma sagittifolium*). *International Biodeterioration and Bulletin* 13(1):5–8.
21. Gollifer, D. E., and R. H. Booth. 1973. Storage losses of taro corms in the British Solomon Islands Protectorate. *Ann. Appl. Biol.* 73:349–356.
22. Posnette, A. F. 1945. Root-rot of cocoyams (*Xanthosoma sagittifolium* (L.)). *Tropical Agriculture, Trinidad* 22(9):164–170.
23. Baybay, D. S. 1922. Storage of some root crops and other perishable farm products. *Philippine Agriculture* 10:429–430.
24. Rice, R. P., L. W. Rice., and H. D. Tindall. 1990. *Fruit and Vegetable Production in Warm Climates*. London: The MacMillan Press.
25. Baryeh, E. A. 1993. Infestation, damage and grading of cocoyam. *Agricultural Mechanisation in Asia, Africa and Latin America* 24(2):43–46, 50.
26. IRETA. September, 1997. Postharvest systems for improved quality of Pacific Island export taro. *IRETA's South Pacific Agricultural News*, p. 7.
27. Been, B. O., J. Marriott, and C. Perkins. 1975. Wound periderm formation in dasheen and its effects on storage. In *Proceedings of a Meeting of the Caribbean Food Crop Society held in Trinidad*, p. 13.
28. Baumgardner, R. A., and L. E. Scott. 1963. The relation of pectin substances to firmness of processed sweet potatoes. *Proc. Amer. Soc. Hort. Sci.* 83:629.
29. Booth, R. H. 1974. Postharvest deterioration of tropical root crops: Losses and their control. *Trop. Sci.* 16:49.

30. Agbor-Egbe, T. A. 1989. Study of the composition and changes occurring during storage of a range of edible aroids. Ph.D. diss. University of Reading, U.K.
31. Agbo-Egbe, T., and J. E. Rickard. 1991. Study on the factors affecting storage of edible aroids. *Ann. Appl. Biol.* 119:121–130.
32. Rickard, J. E. 1981. Biochemical changes involved in post-harvest deterioration of cassava roots. *Trop. Sci.* 23:235.
33. Plucknett, D. L., and M. S. White. 1979. Storage and processing of taro in the Peoples Republic of China. In *Small-scale Processing and Storage of Tropical Root Crops*, ed. D. L. Plucknett, pp. 119–123, Westview Trop. Agr. Series, no. 1. Boulder, Colorado: Westview Press.
34. Jackson, G. V. H., D. E. Golifer, J. A. Pinegar, and F. J. Newhook. 1979. The use of fungicides against post-harvest decay of stored taro in the Solomon Islands. In *Small-scale Processing and Storage of Tropical Root Crops*, ed. D. L. Plucknett, pp. 130–150, Westview Trop. Agr. Series, no. 1. Boulder, CL: Westview Press.
35. Rickard, J. E. 1983. Post-harvest management of taro (*Colocasia esculenta* var *esculenta*). *Alafua Agric. Bull.* 8:43.
36. Thompson, A. K. 1996. *Postharvest Technology of Fruit and Vegetables*. Oxford: Blackwell Science.
37. Gooding, H. J., and J. S. Campbell. 1961. Preliminary trials of West African Xanthosoma cultivars. *Tropical Agriculture (Trinidad)* 38:145.
38. Snowdon, A. L. 1991. *A Colour Atlas of Postharvest Diseases and Disorders of Fruits and Vegetables*, vol. 2: *Vegetables*. London: Wolfe Scientific.
39. Wardlaw, C. W. 1937. Tropical fruits and vegetables: An account of their storage and transport. Low Temperature Research Station, Imperial College of Tropical Agriculture, Trinidad, Memoir 7.
40. SeaLand. 1991. *Shipping Guide to Perishable*. Iselin, NJ: SeaLand Service Inc.
41. Lutz, J. M., and R. E. Hardenburg. 1968. The commercial storage of fruits, vegetables and florist and nursery stocks. U.S. Department of Agriculture, Agriculture Handbook 66.
42. Pantastico, E. B., ed. 1975. *Postharvest Physiology, Handling and Utilisation of Tropical and Sub-tropical Fruits and Vegetables*. Westpoint, CT: AVI Publishing.
43. *Guide to Food Transport: Fruit and Vegetables*. 1989. Mercantilia Publishers.
44. Wilson, J. E. 1983. Storage of taro corms and leaves. *Alafua Agric. Bull.* 8(2):35–37.
45. Quevedo, M. A., R. T. Sanico, and M. E. Baliao. 1991. The control of post-harvest diseases of taro corms. *Trop. Sci.* 31:359.
46. Quevedo, M. A., and A. D. Ramos. 1988. Storage medium for taro corms. *Radix* 10:6.
47. Pardales, J. R., R. S. de la Pena, and F. M. Melchor. 1982. Effects of temperature and methods of preparation on the storability of upland taro corms. *Radix* 4:12.
48. Quevedo, M. A., and A. D. Ramos. 1992. Method of corm preparation for storage of taro corm. *Trop. Science* 32:121.

49. Adams, H., A. Pattanjilidal, and Clark. 1985. Effects of metalaxyl and benomyl on post-harvest decay of corms of dasshen *Colocasia esculenta* (L.) Schott. In *Proceedings of the 7th Symposium of the International Society for Tropical Root Crops*, Guadeloupe.
50. Burton, C. L. 1970. Diseases of tropical vegetables on the Chicago market. *Trop. Agric. Trinidad* 47:303–313.
51. O’Hair, S. K., and M. P. Asokan. 1986. Edible aroids: Botany and horticulture. *Horticultural Reviews* 8:43–99.
52. Plucknett, D. L. 1983. Taxonomy of the genus *Colocasia*. In *Taro: A Review of Colocasia esculenta and its Potentials*, ed. J. K. Wang. Honolulu: University of Hawaii Press.
53. Rhee, J. K., and M. Iwata. 1982. Histological observations on the chilling injury of taro tubers during cold storage. *J. Jpn. Soc. Hortic. Sci.* 51:362.
54. Wang, J., ed. 1983. *Taro A Review of Colocasia esculenta and its Potentials*. Honolulu: University of Hawaii Press.
55. Payne, J. H., G. J. Ley, and G. Akau. 1941. Processing and chemical investigation of taro. *Hawaii Agr. Exp. Sta. Bull.* 393, Orono, ME.
56. Sherman, G. D., G. W. Duernberg, H. Seagrave-Smith, and T. Shaw. 1952. Food processor’s handbook for Hawaiian fruits and vegetables. *Hawaii Agr. Expt. Sta. Progress Notes* No. 81.
57. Moy, J. H., and B. B. Lee Loy. 1969. Shelf life extension of poi by gamma irradiation. *Nucl. Sci. Abst.* 23:1039.
58. Ooka, J. J. 1983. Taro diseases. In *Taro: A Review of Colocasia esculenta and its Potentials*, ed. J. Wang, pp. 236–257. Honolulu: University of Hawaii Press.
59. Coursey, D. G., and D. Halliday. 1975. The edible aroids. *World Crops* 20:25–30.
60. Tang, C. S., and W. W. Sakai. 1983. Acridity of taro and related plants in Araceae. In *Taro: A Review of Colocasia esculenta and its Potentials*, ed. J. Wang, pp. 148–164. Honolulu: University of Hawaii Press.
61. Carpenter, J. R., and W. E. Steinke. 1983. Animal feed. In *Taro: A Review of Colocasia esculenta and its Potentials*, ed. J. Wang, pp. 268–300. Honolulu: University of Hawaii Press.
62. Peters, F. E. 1958. The chemical composition of South Pacific foods. South Pacific Commission Technical Paper 115.
63. Miller, C. D. 1929. Food values of breadfruit, taro leaves, coconut and sugar cane. *Bernice P. Bishop Mus. Bull.* 64:1–23.
64. de la Pena, R. S. 1981. Unpublished interim report on the response of taro top yield to cutting interval, time to initial cutting, and fertilizer. Coll. Trop. Agr. and Human Resources, Univ. of Hawaii.
65. Moore, L. A. 1962. Grass-legume silage. In *Forages*, ed. H. D. Hughes, M. E. Heath, and D. S. Metcalfe, pp. 535–546. Ames, IA: Iowa State University Press.
66. McCullough, M. E., ed. 1978. *NFIA Literature Review on Fermentation of Silage: A Review*. West Des Moines, IA. Grabs-in-Aid Committee, National Feed Ingredients Association.

67. Brierem, K., and O. Ulvesli. 1954. Meld. Norg. *Landhr-Hogstk.* 34:373–479.
68. Wang, J. K., W. E. Steinke, and J. R. Carpenter. 1981. Food, feed and fuel from taro. Paper presented at the Int. Cong. on Agricultural Engineering and Agro-Industries in Asia, 10–13 November, Bangkok, Thailand.
69. Anigbogu, N. M. 1995. Taro as a substitute for corn in broiler rations. *IITA Tropical Root and Tuber Crops Bulletin* 8(2):89.
70. Diongzon, W. E. E. 1981. The future of taro genetic improvement. *Radix* 3:1.
71. Galvaz, C. F. 1980. Root crops flour: Successful substitute for wheat flour in the soy sauce production. *Radix* 1, July–Dec.
72. Jamora and S. Danilo. 1975. Gabi: Root-crops for profit. *Agric. Publishing Series* 44:6–8.
73. Anigbogu, N. M. 1996. Economic costs of using taro (*Colocasia esculenta* Linn.) in broiler rations. *IITA Tropical Root and Tuber Crops Bulletin* 9(1):8–10.
74. Coursey, D. G. 1968. The edible aroids. *World Crops* 20:25–30.
75. Oyenuga, V. A. 1968. *Nigeria's Foods and Feeding Stuffs*. Ibadan, Nigeria: University of Ibadan Press.
76. Higashihara, M., M. Umeki, and T. Yamamoto. 1975. Isolation and some properties of taro root starch. *Denpun Kagaku (J. Japan Soc. Starch Sci.)* 22:61–65.
77. Radley, J. A. 1940. *Starch and its Derivatives*. London: Chapman and Hall.
78. Griffin, G. J. L., and J. Wang. 1983. Industrial uses. In *Taro: A Review of Colocasia esculenta and its Potentials*, ed. J. Wang, pp. 301–302. Honolulu: University of Hawaii Press.
79. Modi, J. D., and P. R. Kulkarni. 1976. New starches: The properties of the starch from *Amaranthus paniculatus*, Linn. *Acta Alimentaria* 9:399.
80. Goering, K. J., and B. De Haas. 1972. New starches: VIII. Properties of the small granule starch from *Colocasia esculenta*. *Cereal Chem.* 49:712–719.
81. Schoch, T. J. 1964. Iodometric titration of amylose. In *Methods in Carbohydrate Chemistry*, vol. 4A, ed. R. I. Whistler, pp. 157–160. New York: Academic Press.
82. Gaiind, K. N., K. S. Chopra, and A. C. Dua. 1968. Study of the mucilages of corm and tuber of *Colocasia esculenta* Linn: I. Emulsifying properties. *Indian J. Pharm.* 30:208–211.
83. Gaiind, K. N., K. C. Chopra, and A. C. Dua. 1969. Mucilages of corm and tuber of *Colocasia esculenta* Linn: II. Binding properties. *Indian J. Pharm.* 31:156–158.
84. Phillips, T. P. 1978. Economic implications of new techniques in cassava harvesting and processing. In *Cassava Harvesting and Processing*, ed. E. J. Weber, J. H. Cock, and A. Chouinard, pp. 66–74. Proceedings of a workshop held at CIAT, Cali, Colombia, 24–28 April.
85. Milfont, W. N. 1978. Prospects of cassava fuel alcohol in Brazil. In *Cassava Harvesting and Processing*, ed. E. J. Weber, J. H. Cock, and A. Chouinard, pp. 46–48. Proceedings of a workshop held at CIAT, Cali, Colombia, 24–28 April.
86. Brown, L. R. 1980. Food or fuel: New competition for the world's cropland. Worldwatch Paper 35. Washington, DC: Worldwatch Institute.

87. Griffin, G. J. L. 1979. Non-food application of starch with special reference to potential uses of taro. In *Small-scale Processing and Storage of Tropical Root Crops*, ed. D. L. Plucknett, pp. 275–299. Westview Tropical Agriculture Series, no. 1. Boulder, CO: Westview Press.
88. Griffin, G. J. L. 1974. Biodegradable fillers in thermoplastics. *Amer. Chem. Soc. Adv. Chem.* 134:159–170.
89. Plucknett, D. L., ed. 1979. *Small-scale Processing and Storage of Tropical Root Crops*. Westview Tropical Agriculture Series, no. 1. Boulder, CO: Westview Press.
90. Simmonds, H. R., C. Ellis, and C. W. S. Bigelow. 1943. *Handbook of Plastics*. London: Chapman and Hall.

3 Fruit and Vegetables

C. J. Studman, Co-Editor

3.1 Fruit and Vegetable Quality

C. J. Studman

3.1.1 Importance of Fruits and Vegetables, and Quality Considerations

Fruit and vegetables form an essential part of a balanced diet. They are an important part of world agricultural food production, even though their production volumes are small compared with grains (Table 3.1). Fruit and vegetables are important sources of digestible carbohydrates, minerals, and vitamins, particularly vitamins A and C (Table 3.2). In addition they provide roughage (indigestible carbohydrates), which is needed for normal healthy digestion [1].

Technology has enabled exporters to supply markets around the world with high quality product, and in some cases to introduce and develop new markets. This has included introducing new crops and often defining the quality standards for these crops. The agricultural engineer has an important role to play in enabling producers to define and meet quality requirements.

Quality

Where fresh food is concerned, most people can decide the difference between a product that is of good quality and one that is not. Quality is an increasingly important factor in the production and marketing of biological products. Consumers in many countries are becoming more discerning as their affluence increases, and would-be suppliers of products must meet these demands if they are to maintain or increase market share. However, what do we mean by quality? Its assessment is very subjective and depends on a person's viewpoint and preferences. There are three key areas to consider: its meaning, measurement, and maintenance.

3.1.2 Meaning of Quality

In the ISO 9000 standard (developed by the International Standards Organisation), quality is defined as “the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs” [5, 6]. Kader [7] defines it for fruit and vegetables as “the combination of attributes or properties that give them value in terms of human food.”

Table 3.1. Total world production of various crops

Fruit	Production (10 ⁶ tonne)
Grapes	60
Oranges	54
Bananas	113 ^a
Apples	40
Mangos	15
Pineapples	10
Pears	10
Plums	6.5
Peaches	8.6
Papaya	3.9
Strawberries	2.4
Apricots	2.2
Avocados	1.5
Rice	530 ^a
Wheat	530 ^a
Coarse grains	885 ^a
Coffee	5.4 ^a
Tea	2.6 ^a
Meat	190 ^a

Sources: [1–3].

^a 1994 data [3]. All other data 1990 [1, 2].

Quality may be equated to meeting the standards required by a selective customer. In this context the customer is the person or organization receiving the product at each point in the production chain. This is important, because quality is perceived differently depending on the needs of the particular customer. The customer purchasing the fruit for consumption usually judges the product on the basis of its appearance, including its shape, firmness, and color, as well as freedom from defects such as spots, marks, or rots. The consumer will judge the fruit on its eating quality (ie, taste or texture) as well as its keeping qualities in the home. The packing shed operator may be much more concerned about the percentage of good fruit in a batch, and how easy it is to handle and grade. There are many different factors that can be included in any discussion of quality (Table 3.3). Quality characteristics of various crops are given in the Appendix (Table 3.A1).

If something is not a quality product, this implies that the product does not meet a certain standard that has been adopted by the consumer. In this case, the market price is adversely affected [8]. Conversely, if a product is perceived to be a quality product, then it sells for a better price [9].

Food Safety, Hygiene, and Quarantine Factors

Food safety is a major factor in quality [10]. There are several possible problems.

Naturally Occurring Contaminants

These include cyanogenic glucosides in lima beans and cassava, nitrates and nitrites in leafy vegetables, oxalates in rhubarb and spinach, thioglucosides in cruciferous

Table 3.2. Approximate composition of major fruits grown in the world

	Water (%)	Energy (kcal/100 g)	Protein (%)	Fat (%)	Carbo-hydrate (%)	Minerals (%)	Calcium (mg/100 g)	Phos-phorus (mg/100 g)	Iron (mg/100 g)	Magnesium (mg/100 g)	Vitamin A (IU)	Thiamine (mg/100 g)	Riboflavin (mg/100 g)	Nicotinic acid (mg/100 g)	Ascorbic acid (Vit C) (mg/100 g)
Grapes	81.6	67	1.3	1.0	15.7	0.4	16	12	0.4	13	100	0.05	0.03	0.3	4
Oranges	86.0	49	1.0	0.2	12.2	0.6	41	20	0.4	11	200	0.10	0.04	0.4	50
Bananas	75.7	85	1.1	0.2	12.6	0.6	8	26	0.7	33	190	0.05	0.06	0.7	10
Apples	84.4	58	0.2	0.6	14.5	0.3	7	10	0.3	8	90	0.03	0.02	0.1	4
Mangos	83.4	59	0.5	0.2	15.4	0.4	12	12	0.8	—	630	0.05	0.06	0.4	53
Pineapples	85.4	52	0.4	0.2	13.7	0.3	18	8	0.5	—	15	0.08	0.04	0.2	61
Pears	83.2	61	0.7	0.4	15.3	0.4	8	11	0.3	7	20	0.02	0.04	0.1	4
Plums	81.1	66	0.5	0.2	17.8	0.4	18	17	0.5	9	300	0.08	0.03	0.5	5
Peaches	89.1	38	0.6	0.1	9.7	0.5	9	19	0.5	10	1330	0.02	0.05	1.0	7
Papaya	90.7	32	0.5	0.1	8.3	0.4	20	13	0.4	—	110	0.03	0.04	0.3	46
Apricots	85.3	51	1.0	0.2	12.8	0.7	17	23	0.5	12	2700	0.03	0.04	0.6	10
Avacados	74.4	80.5	1.8	20.6	—	1.2	14	27	0.7	23	—	0.07	0.12	1.9	11
Strawberries	89.9	37	0.7	0.5	8.4	0.5	21	21	1.0	12	60	0.03	0.07	0.6	59

Sources: [1, 4].

Table 3.3. Quality factors for fresh fruit and vegetables

Hygiene and quarantine factors
Quarantine: passenger parasites (larvae, pupae, adults)
Consumer safety: natural toxicants, contaminants (spray residues, heavy metals, etc.), mycotoxins (fungi, etc.), microbial contamination
Cosmetic appearance
Size: weight, volume, dimensions
Shape: regularity, length, diameter
Surface texture: smoothness, waxiness, gloss
Color: uniformity, intensity, spectral
Physical defects: splits, cuts, dents, (apparent) bruises
Pathological/entomological: scale, fungi, insects
Physiological: browning, genetic defects
Texture and flavor factors
Texture: firmness (hardness/softness), crispness, juiciness, mealiness (grittiness), fibrousness (toughness)
Flavor: sweetness, sourness (acidity), astringency, bitterness, aroma (volatile compounds), off flavors off odors
Nutritional: dietary fiber, cancer inhibitors/accelerators, carbohydrates, proteins, lipids, vitamins, minerals

Adapted from [7].

vegetables, and glycoalkaloids (solanine) in potatoes [11]. Traditional processing and cooking practices usually remove the bulk of these contaminants, but there could be problems if new consumers are introduced to new crops.

Natural Contaminants

Mycotoxins (fungal toxins), bacterial toxins, and heavy metals occur naturally and can be present in some crops.

Synthetic Toxicants

Agricultural chemical residues, and introduced environmental pollutants such as lead, can be a problem unless production systems are controlled and monitored carefully. In developed countries levels of these usually are very low (e.g., in the United States in the mid-1990s less than 1% of products showed excessive traces [11]). In many countries consumers are very concerned about the levels of chemical-spray deposits found in and on fresh products. For this reason food imports often are subjected to very careful chemical analysis. Evidence of pesticide residues above acceptable levels, or the presence of unapproved or banned spray deposits, renders entire shipments of otherwise sound crops unsaleable. Growers therefore must be especially concerned with ensuring that no illegal sprays are used on crops, and that withholding periods are strictly enforced. Normal practice is to maintain a spray diary, which indicates what sprays were used on the crop at what times prior to harvest.

Microbial Contamination

Viewed by most health professionals as the most serious health concern, microbial contamination is viewed by consumers as being less important than chemical toxicants. Bacteria can be introduced onto fresh fruit and vegetables through the use of untreated organic fertilizers (e.g., manure), or through insufficiently treated wastewater. Inadequate hygiene standards in packing sheds and anywhere else in the food chain can also cause problems. The problem is exacerbated because fruit and vegetables often are eaten fresh. Washing fresh produce is a help, but the water used should also be clean and free of contaminants.

Clearly any biological food product must be safe to eat and must not present a risk to the consumer, or to the importing country. Fruit and vegetables are always at risk of carrying disease, insects, or larvae that could cause major problems if introduced to countries in which they are not present. Requirements vary between countries, depending on whether the country is free of a particular disease. America and most other markets are concerned about fire blight, leaf roller, Mediterranean fruit fly, and nysius; Japan has strict requirements concerning codlin moth. New Zealand and Australia are particularly concerned about fruit fly because an infestation prevents them exporting products to key international markets. Some insects are passengers rather than parasites of the crop in question. The nysius insect is a serious threat to wheat crops and may be transported in fruit cartons, even though it does not affect the fruit itself.

Controls must be in place to ensure that such problems are absent from produce. These require careful control of packing sheds and cool stores, including the use of lighting that does not attract insects. Often orchard spraying is a major method of control of parasites, but this introduces concerns about chemical residues on fruit. Consumers of the 1990s are far more conscious of these issues than any previous generation, and food safety is likely to be the most important quality factor in the 21st century [10].

Cosmetic Appearance

There is no doubt that in most developed markets the appearance of fruit and vegetables has a major influence on perceived quality. Quality is defined in terms of shape, color, size, uniformity, and absence of apparent defects [11]. Thus, in the case of bruising in apples, the surface size and appearance of the bruise is more important in the fresh fruit market than the volume of the bruise. Bruises may be present, but if they cannot be seen, they do not appear to be of importance to the market. On the other hand, fruit that appears to be bruised or marked, but is not, loses value.

Shape and appearance are important quality factors: The cross-section of a kiwifruit is an attractive pattern, and a strong market was developed for this fruit as a decoration for salads and main dishes in high-quality restaurants.

Taste, Texture, and Nutritional Factors

Table 3.2 lists compositional components of fruit and vegetables. Vegetables are high in mineral substances including K, Na, Ca, Mg, Fe, Mn, Al, P, Cl, and S. Particularly important are their contents of K, Fe, and Ca. Spinach, carrots, cabbage, and tomatoes are particularly rich in minerals. Vegetables with high Ca include green beans, cabbage, onions, and beans. Fruits rich in minerals include strawberries, cherries, peaches and

Table 3.4. Specific sensitivity and stability of nutrients

	Neutral (pH = 7)	Acid (pH < 7)	Alakline (pH > 7)	Air or Oxygen	Light	Heat	Cooking Losses, Range (%)
Vitamins							
Beta Carotene (Vit A)	S	U	S	U	U	U	0–40
Ascorbic acid (Vit C)	U	S	U	U	U	U	0–100
Biotin	S	S	S	S	S	U	0–60
Carotenes (pro A)	S	U	S	U	U	U	0–30
Choline	S	S	S	U	S	S	0–5
Cobalamin (B12)	S	S	S	U	U	S	0–10
Vitamin D	S		U	U	U	U	0–40
Essential fatty acids	S	S	U	U	U	S	1–10
Folic acid	U	U	S	U	U	U	0–100
Inositol	S	S	S	S	S	U	0–95
Vitamin K	S	U	U	S	U	S	0–5
Niacin (PP)	S	S	S	S	S	S	0–75
Panthothenic acid	S	U	U	S	S	U	0–50
Para Amino							
Benzoic acid	S	S	S	U	S	S	0–5
Vitamin B6	S	S	S	S	U	U	0–40
Riboflavin (B2)	S	S	U	S	U	U	0–75
Thiamin (B1)	U	S	U	U	S	U	0–80
Tocopherols	S	S	S	U	U	U	0–55

Source: [12].

Note: U = unstable; S = stable.

raspberries. Citrus is high in vitamin C (ascorbic acid), as are papaya, mango, kiwifruit, tomatoes, cabbage and green peppers. Apples are high in Fe, while vitamin A is provided through beta-carotene found in orange and yellow vegetables and green leafy vegetables. Vitamin B also is found in fruits and vegetables in significant quantities.

Many nutrients are destroyed by heat (Table 3.4). Fresh fruit and vegetables are therefore particularly beneficial to a healthy diet. Modern food-processing operations are more effective in preventing excessive nutrient losses, reducing them to around 25% or less [12].

Although taste and nutritional value may appear to be what quality is all about, the realities of the marketplace suggest that these factors are frequently less crucial than one might expect. The final consumer may be the only person who cares very much about taste. In theory, if the end consumer is not satisfied this results in an unsatisfactory commercial result for the product. However, because purchasing precedes consumption, and marketing seeks to modify previously held opinions, at worst there is a substantial time delay before the taste of a product destroys its commercial viability.

Taste and texture preferences can affect the marketability of some crops. For example the apple cultivar “Fuji” was originally developed as a sweet-tasting apple, with a center that had a glassy appearance (water core). This region was particularly sweet and was therefore regarded as a mark of quality in Japan. However, the glassy appearance was not appreciated by American consumers, who viewed it as a defect in the texture of the fruit.

Some important conclusions can be reached from these comments. Quality standards are affected by international and cultural preferences [13]. Standards can be affected by cultural changes or by strong marketing in the media. They may also change over time to reflect increased consumer awareness of quality factors.

3.1.3 Measurement

For each factor, some objective means of measurement is required [14], and the agricultural engineer has an important role to play in the development of suitable testing methods. Measures of actual quality and predicted quality at some time in the future are needed.

The only true test of quality is the response of the consumer. Eating quality can be assessed most accurately by using taste panels. These consist of a selection of customers from the market who are trained to assess the quality attributes being examined. This is a very expensive and time-consuming task. Furthermore, it can only be attempted when the product has reached the eating stage of its lifetime, by which time it is too late to do much about the quality. Hence, taste panels cannot be used easily as part of the production process. Instead it is necessary to resort to readily usable test methods, which may involve simple or complex equipment. The reliability and value of these methods depends on how well they correlate with the views of consumers, rather than the level of scientific objectivity of the test.

Producers require measurements that are rapid and repeatable and give a good indication of the quality of the product, in terms of the expectations of the customer. Measurements very often are given as indices, which can be used as guides to desirable quality attributes such as taste, texture, storage life, and maturity. Any appropriate index that is found to be a suitable guide to a quality attribute can be used, and so the range of indices used is quite remarkable. In some cases visual observation is adequate; in others physical or chemical tests have been developed, often with limited scientific basis. These now serve as industry standards. Tables 3.5 and 3.6 list quality indices used for a wide range of crops for both harvest maturity and for postharvest assessment [11, 12, 14].

In some cases standards suited to one crop (or variety or product grown in one country) have been adopted as quality criteria for other similar crops, even though growing conditions and crop behavior may be quite different. Unfortunately for the producer it is necessary to meet these standards even though they may at times appear to be illogical or unreasonable, at least until the market can be persuaded to review and modify the indices.

Measurement may be required at several different points in the postharvest chain. Particularly important points are when decisions must be made about the timing of operations. Therefore tests for harvest maturity are especially important. Many of these are crop-specific, based on particular physiological changes as the fruit or vegetable matures, and are no longer useful after harvest. Other tests are useful both before and after harvest. Grading criteria during sorting and packing, and quality checking in storage, can be very important. Tests also may be desirable at out-turn (unloading on arrival at the destination market), at retail, and in the home prior to consumption. In selecting a method the purpose for which the test is needed should be considered.

Table 3.5. Maturity indices and methods of determination for selected fruits and vegetables

Index	Methods of Determination	Subjective	Objective	Destructive	Non-destructive	Examples
Elapsed days from full bloom	Computation		x		x	Apples, pears
Mean heat units	Computation from weather data		x		x	Peas, sweet corn
Dev. of abscission layer	Visual or force of separation	x	x		x	Muskmelon
Surface structure	Visual	x			x	Cuticle formation on grapes and tomatoes, netting of muskmelons, gloss or wax development
Size	Various measuring devices, weight		x		x	All fruits and many vegetables
Specific gravity	Density gradient solutions, flotation techniques		x		x	Cherries, water melons, potatoes
Shape	Dimensions ratio charts	x	x		x	Angularity of banana fingers, full cheeks of mango, compactness of broccoli and cauliflower
Solidity	Feel, bulk density, γ -rays, X-rays	x	x		x	Lettuce, cabbage, brussell sprouts
Textural properties						
Firmness	Firmness testers, deformation		x	x		Apples, pears, stone fruits
Tenderness	Tenderometer		x	x		Peas
Toughness	Texturometer, fibrometer (also chemical methods for polysaccharides)		x	x		Asparagus
Color						
External	Light reflectance, visual color charts	x	x		x	All fruits and many vegetables
Internal	Light transmittance, delayed light emission,		x		x	All fruits and many vegetables Flesh color of some fruits, e.g., mangoes

Table 3.5. (Continued)

Index	Methods of Determination	Subjective	Objective	Destructive	Non-destructive	Examples
Internal structure	Light transmittance, delayed light, emission, visual examination	x	x		x	Jelly-like formation in tomatoes Kiwifruit; apple pip color; jelly-like formation in tomatoes; flesh color of some fruits, e.g., mangoes
Compositional factors						
Total solids	Dry weight		x	x		Avocados, kiwifruit
Starch content	KI test, other chemical tests		x	x		Apples, pears
Sugar content	Hand refractometer, chemical tests		x	x		Apples, pears, stone fruits, grapes, kiwifruit
Acid content (or sugar/acid ratio)	Titration, chemical tests		x	x		Citrus, pomegranates, papaya, melons
Juice content	Extraction, chemical tests		x	x		Citrus
Oil content	Extraction, chemical tests		x	x		Avocados
Tannin content	Ferric chloride test, chemical tests		x	x		Persimmons, dates
Internal ethylene	Gas chromatography		x	x		Apples, pears

Source: Modified from [11].

Measurement methods can be destructive or nondestructive. Destructive tests include tests that are themselves nondestructive but require samples to be cut from products. Tests can be further roughly grouped (according to the method used), into mechanical, visual (by human eye or by instrument), electrical, chemical, or biological. In some cases several methods may be combined to give an overall quality index.

Mechanical Destructive Indices

Firmness measurements in fruits and vegetables have been used for over 60 years as guides to the quality of the product [15–17]. Firmness meters attempt to record a value that represents how easily the product can be deformed under a pressure applied to a limited area of its surface (or more simply what happens when you squeeze it). They range from laboratory systems costing thousands of dollars to much cheaper handheld devices, which can be used in the field [16–18]. The devices have been applied to a wide range of fruits and are often the main test specified to establish the acceptability of the product for a particular market or storage condition. Harker *et al.* recently have completed an extensive review of texture measurement [18].

Table 3.6. Methods for evaluating quality

	Measurement	Equipment	Notes
Appearance			
Size	Dimensions	Sizing rings, calipers	Mass or no per-unit mass
	Weight	Scales	Mass or no per-unit mass
	Volume	Water displacement	
Shape	Ratios of dimensions	Diagrams, pictures	
Color	Uniformity, intensity		
	Visual matching	Color charts, guides	
	Reflectivity	Spectrophotometer, color-difference meters	
	Transmission	Light-transmission meter	Internal defects
	Delayed light emission	Meter	Related to chlorophyll
	Pigment determination	Chemical	Chlorophylls, caretonoids, flavonoids
Gloss (bloom, finish)	Wax platelets: amount, structure, arrangement	Gloss meter, visual	
External defects	Incidence, severity	Charts, scales	
Internal defects	Incidence, severity	Charts, scales, NMR, MRI, X-rays	
Texture			
Tissue strength	Firmness, softness	Penetrometer (Effegi, Magness Taylor), Massey twist tester, texture analyzer	See text
Fibrousness, toughness	Shear force, cutting resistance, fiber/lignin content	Texture analyzer, Massey twist tester, fibrometer, chemical	
Juiciness, succulence	Water content (turgidity), extractable juice (succulence)	Weight, crushing system	
Sensory attributes	Grittiness, chewiness, mealiness, etc.	Taste panel	
Flavor			
Sweetness	Sugar, soluble solids	Chemical, indicator papers, refractometer	
Sourness	Juice pH, titratable acidity	pH meter, chemical	
Astringency, bitterness		Taste panel, chemical	
Aroma	Volatile components	Taste panel, chemical, GC	
Nutritional value	Carohydrates, dietary fiber, proteins, amino acids, lipids, fatty acids, vitamins, minerals	Chemical	
Food safety	Natural and synthetic toxicants and contaminants	Thin-layer, gas, and high-pressure liquid chromatography	HACCP techniques
	Microbial contaminants	Biological incubation methods, plate counts	

Source: Modified from [11].

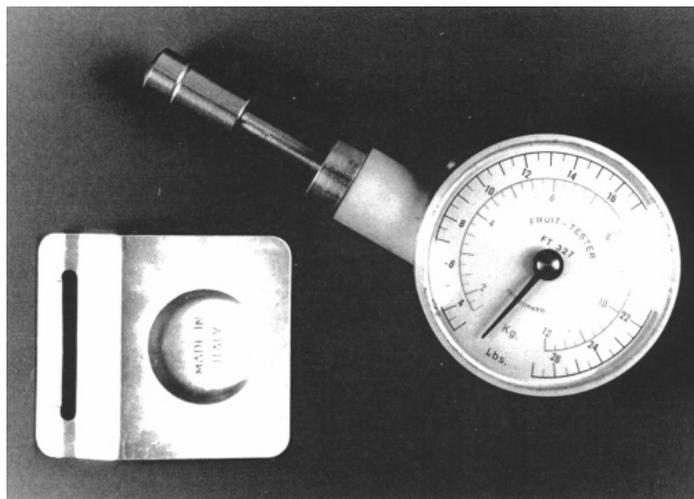


Figure 3.1. Effigi penetrometer.

Penetrometer

The most common device used to assess firmness is the penetrometer. This has a cylindrical probe, the end of which is pushed into the object to be measured. The force required to give a predetermined penetration is recorded. In most fruit a section of the skin is removed first to expose the flesh. The penetrometer then gives an index of the firmness of the product tissue. Several versions have been developed. The Magness Taylor penetrometer is forced into the tissue, compressing a spring. When the probe has penetrated to a specified depth, the reading is taken from the spring compression. An alternative, more compact version is the Effigi penetrometer, which has a coiled spring so that the force can be read off a dial (Fig.3.1). The results from both these devices are quickly obtained, but values are very dependent upon the operator, to the extent that variations in readings of 200% have been recorded between different operators [19]. The Effigi can be mounted easily into a drill press to reduce operator dependency. Dedicated automated testers [13], or universal testing machines, remove the operator bias altogether. These devices suffer from increased cost and loss of portability. The penetrometer still is used widely as an internationally recognized index of handling quality, storage life, and maturity in many fruit crops.

The simplicity, speed of testing, and robustness of the equipment make the penetrometer attractive to the fruit and vegetable industry. Moreover the test simulates the “feel” or firmness of the product. Cylinder heads are usually either 11 or 8 mm in diameter. However, it is not possible to interchange the heads, as the results from the two sizes are not consistent. In apples and pears the larger size is normally used, while the 8-mm probe is used on smaller fruit.

Theoretical analyses have been attempted. Bourne [20] gave the following formula:

$$F = K_c A + K_s P + C \quad (3.1)$$

where F is the puncture force, K_c is the compression strength, K_s is the shear strength, A is the area of the punch, P is the perimeter of the punch, and C is a constant. More detailed theoretical and experimental studies have been conducted, which have shown that the main component of F is due to compression [21].

Other problems of the penetrometer include its limited range, especially for fruit that softens dramatically. There is a wide scatter in the readings among similar fruit, and usually at least 20 samples are required for one value. In softer fruit removal of the skin before testing can introduce significant errors, depending on the thickness of the slice. The indenter measurement is not easily modeled in theoretical terms and does not correlate well with other mechanical measurements. Values are affected by surface properties, whereas in some fruit the texture at depth would provide a more reliable quality indicator. Duprat *et al.* [16] have advocated using the firmness measured at 5 to 9 mm depth as a standard rather than at the surface. This requires a texture analyzer rather than an ordinary penetrometer to measure the force as a function of depth.

Pea Tenderometer

This device is widely recognized as the standard measure for pea tenderness. A sample of peas is loaded into the testing chamber, and a set of blades cuts through the sample, using a rising pendulum weight to measure the force required [22, 23].

Texture Analyzers

Research laboratories commonly use universal testing machines to determine physical properties of crops. Very low loads are needed, and most machines in engineering laboratories are insufficiently sensitive. It is important to avoid external vibrations of and high stresses on the sample during mounting. For these reasons sensitive universal testing machines have been developed that are dedicated to the measurement of food texture. Modern systems use a computer for control and recording of data, and sophisticated loading cycles can be developed [16].

Indenting heads include a penetrometer cylinder, a spherical indenter, and a flat plate to give compression tests between parallel plattens. One system measures the bursting strength of the skin of tomatoes and the whole-fruit compression resistance in the same test [16]. Measurements can be taken on whole fruits and vegetables or cut samples. Theoretical values can be obtained from stress-strain data, according to the loading geometry. Formulae are given in Table 3.A2 in the Appendix. Tensile tests also can be performed, especially for fibrous products. Shear tests and viscosity measurements also can be used [24, 25]. Common loading cycles include applying a fixed compression distance or a percentage of the fruit diameter. Alternatively the deformation after applying a fixed load for a given time can be determined. For cherries a double-loading test can be used. In this the fruit is loaded, and the load-against-deformation curve is plotted [16]. After a fixed time at maximum load, the load is removed, and after a set time it is reapplied to produce a second force-deformation curve. Differences in areas under the curves indicate tissue recovery. Texture analyzers also can be used for nondestructive measurements, as discussed subsequently.

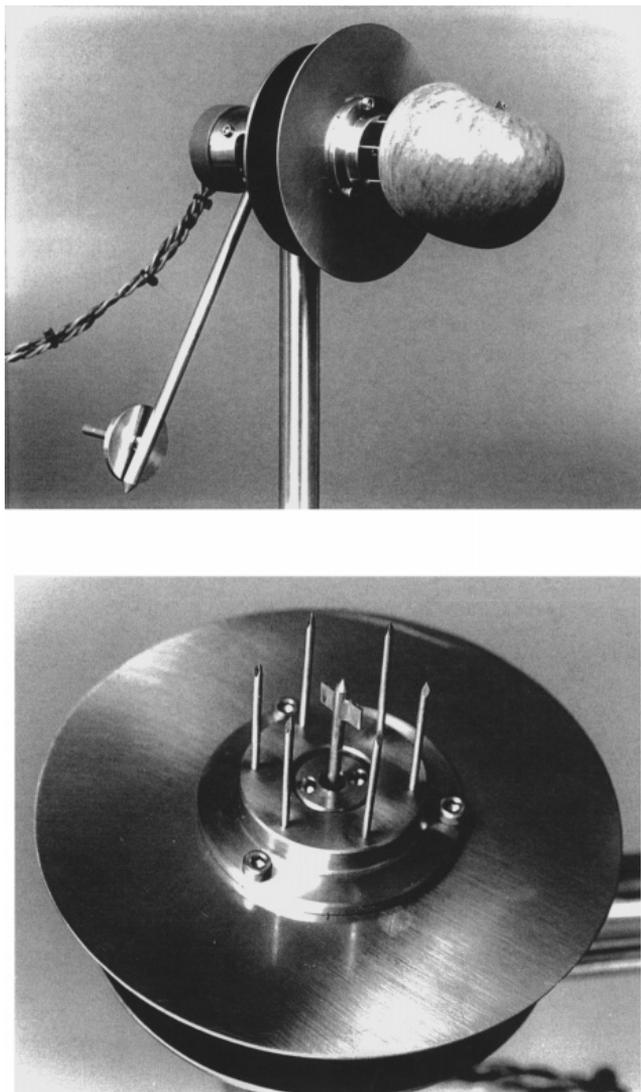


Figure 3.2. Twist tester.

Twist Tester

An alternative destructive tester has been developed in which the fruit is pushed onto a blade mounted on a spindle, so that the blade enters the fruit at a predetermined depth under the skin [26]. The fruit is rotated, so that the blade turns at a fixed depth (Fig.3.2). A rising weight on the end of an arm is used to apply an increasing moment (torque) to the blade, to resist the rotation. Eventually failure of the tissue occurs, and the moment

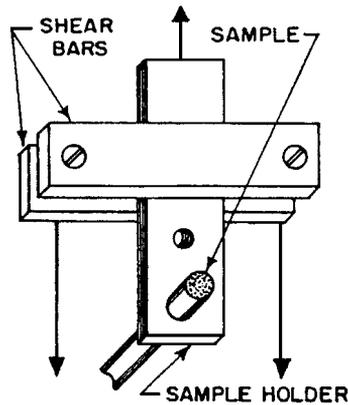


Figure 3.3. Warner Bratzler tester.
(Source: [29])

can be calculated from the angle of the arm. In some versions fruit is rotated by hand, but in other versions the fruit is rotated on a set of pins driven by a motor. Output is determined either by reading the maximum angle to which the pendulum weight is lifted or by recording the angle as a function of time electronically. It has been used successfully to measure the texture of apples, kiwifruit, mangoes, plums, and other fruit [27, 28].

Warner Bratzler

Although primarily designed for meat texture, this test has been used to assess the texture of some stem vegetables (Fig. 3.3). The sample is placed through a hole in a plate, and the plate slides between two other metal plates, shearing through the specimen at the edge of the hole [29].

Gape Test

In some fruits the skin acts as a confining pressure vessel for the internal tissue, which is subject to cell turgor pressure. If the skin is cut from stem end to calyx, the opening of the split after a short period of time can be taken as an index of turgor pressure. The depth of cut must be carefully controlled, and a sharp knife is needed.

Bruise and Damage Susceptibility Testers

Handling quality can be assessed using methods for determining bruise susceptibility of fruit and vegetables. Techniques are discussed in Section 3.3.

Abscission

The point at which fruits and vegetables can be easily detached from their plants is essentially a nondestructive assessment of maturity, but because the measure cannot be undone, it is destructive. The test is simple, and in many crops (e.g., feijoa) mature fruit self-select by detaching from the tree. However, in other crops abscission occurs too late, and their eating or storage quality is poor.

Visual Destructive Tests

Physiological Changes

Some indices require the visual assessment of cut sections of fruit and vegetables. Some fruits (e.g., bananas) change their cross-sectional shape noticeably as they approach maturity, and the cross-sectional area therefore can be used as an index [23]. Other fruits split open as they mature, to give a simple criteria for maturity. Pip, seed, or stone development inside the fruit also is often a good indicator of maturity. In kiwifruit the number of seeds and the uniformity of their distribution around the center are indications of quality. These are affected by pollination at the start of the life of the fruit.

Color

Flesh color is an important determinant of quality and maturity in many crops including melons, mangoes, and squash. Chemical analysis does not enable color estimation: Vegetable and fruit yellowing is often a result of the disappearance of chlorophylls, which allows the yellow–orange xanthophylls and carotenes to become more visible [24]. Blueberry color is determined by anthocyanins, which are red when extracted.

Color can be defined by three parameters. Humans see color differently from electronic equipment, and use different scales. People can distinguish the level of lightness or color intensity of an object, its hue (i.e., its color name such as *red*, *blue*, or *green*), and its chroma (degree of color purity, saturation, brightness, or greyness). Color meters give an absolute determination of color using a standard three-component specification, known as the Hunter Lab scale. This uses lightness (L), red–green character in the absence of yellow or blue (a), and yellow–blue character in the absence of red or green (b) [24]. Thus an increase in yellowness on the Lab scale will result in a greater value of $+b$, while for human perception a more yellow color will result as the hue angle ($\tan^{-1} b/a$) approaches 90 degrees. Thus, using just b values to denote yellowness could cause confusion [24]. It is possible to convert from the L , a , and b measures to the human terms of *lightness*, *hue*, and *chroma* through calculation. An alternative scale, known as the CIE $L^*a^*b^*$ scale is being used more often by researchers. Values are calculated from the following formulae:

$$\begin{aligned} L &= 100Y^{1/2} \\ a &= A(X - Y)/Y^{1/2} \\ b &= B(Y - Z)/Y^{1/2} \end{aligned} \quad (3.2)$$

$$\begin{aligned} L^* &= 116Y^{1/3} \\ a^* &= 500(X^{1/3} - Y^{1/3}) \\ b^* &= 200(Y^{1/3} - Z^{1/3}) \\ \text{for } X, Y, \text{ and } Z &> 0.01 \end{aligned} \quad (3.3)$$

where X , Y , and Z are the tristimulus values divided by the values for a perfectly diffusing surface illuminated with the lighting used, and A and B are chromacity coefficients for the illuminant used (Fig. 3.4).

CIE 1976 L* a* b* (CIELAB)

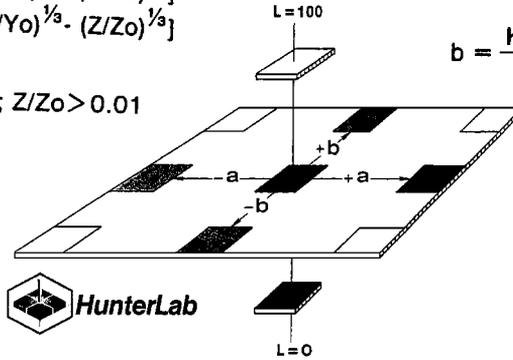
$$L^* = 116 (Y/Y_0)^{1/3} - 16$$

$$a^* = 500 [(X/X_0)^{1/3} - (Y/Y_0)^{1/3}]$$

$$b^* = 200 [(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}]$$

Limited to:
X/X₀; Y/Y₀; Z/Z₀ > 0.01

L, a, b, COLOR SOLID



Where: 1) X, Y, Z are tristimulus values
2) X₀, Y₀, Z₀ are tristimulus values for perfect diffuser for illuminant used
3) K_a, K_b are chromaticity coefficients for illuminant used

Illuminant	X ₀	Y ₀	Z ₀	K _a	K _b
A	109.828	100.000	35.547	185	38
C	98.041	100.000	118.103	175	70
D ₆₅	95.018	100.000	108.845	172	67

HUNTER L, a, b

$$L = 100 (Y/Y_0)^{1/2}$$

$$a = \frac{K_a (X/X_0 - Y/Y_0)}{(Y/Y_0)^{1/2}}$$

$$b = \frac{K_b (Y/Y_0 - Z/Z_0)}{(Y/Y_0)^{1/2}}$$

Figure 3.4. Three-color component diagram. (Source: Hunter Associates)

In commercial practice color charts normally are used. Carefully reproduced color photographs of fruit in the desired state are common, although color paint chips also can be used if the tissue is uniform in texture and color.

Refractometer

Although really a measurement of chemical composition, the levels of soluble solids in fruit and vegetable juices can be determined by measuring the refractive index of the juices. Laboratory and field devices require a small sample of juice placed on a glass cover. The refraction of the light produces an indication on a scale that gives a measure of the soluble solids directly. This is a useful indicator of maturity at harvest time, especially in kiwifruit. Refractometers are low in cost but may require calibration. Measurements may be affected by temperature and delays in carrying out the test after exposing fresh juice.

Electrical Destructive Measurements

Attempts to measure fresh-fruit and vegetable electrical conductivity have been reported in laboratory studies, but these have not been used widely as a measure of quality.

Capacitative and inductive measurements also can be made, using high-frequency electrical signals. Nelson *et al.* [30] studied the dielectric properties of a wide range of fruits and vegetables at 200 MHz and 20 GHz. They concluded that differences were present that were related to maturity of the crop, but that the work was not sufficiently developed to enable maturity indices to be defined.

Electrical measurements have been used to determine moisture content of crops being dried, such as coconut copra. Conductivity is measured by pressing two stainless steel or platinum probes into the product and applying a fixed or alternating voltage. A range of moisture meters is used for grain-moisture assessment, as discussed in other sections of this handbook.

Chemical Tests

General Chemical Assessment

The relative proportions of chemicals in the juices of fruits and vegetables is often a good indicator of quality. Particularly during maturation, there are significant changes in chemical composition, and these can be measured by appropriate analytical means. In avocados oil content is a key maturity indicator (the level depending on the variety). Minimum juice contents for citrus fruits at harvest are listed in Table 3.7.

Thompson [23] points out that because of the buffering capacity of fruit juices, acidity should be measured by titration and not merely by assessing the pH of the fruit.

Starch Test

A common maturity test is the starch level in a fruit (particularly apples and pears), found by cutting the fruit in half along the equator and placing the cut surface in an iodine solution (4% potassium iodide and 1% iodine). The iodine stains the section in regions of high starch but does not affect sugars. The resulting stain pattern can be compared against photographs of standard patterns, and a starch index determined. The pattern depends on the cultivar (Figure 3.5).

Chemical Residues

Normal analytical chemical tests can be used to test for spray residues. Gas chromatographs also are used extensively. These detect the characteristic distribution of molecular weights associated with targeted organic substances [23, 24].

Table 3.7. Minimum percentage juice contents for citrus fruits at harvest

	Juice Content
Navel oranges	30
Other oranges	35
Grapefruit	35
Lemons	25
Mandarins	33
Clementines	40

Source: [23].

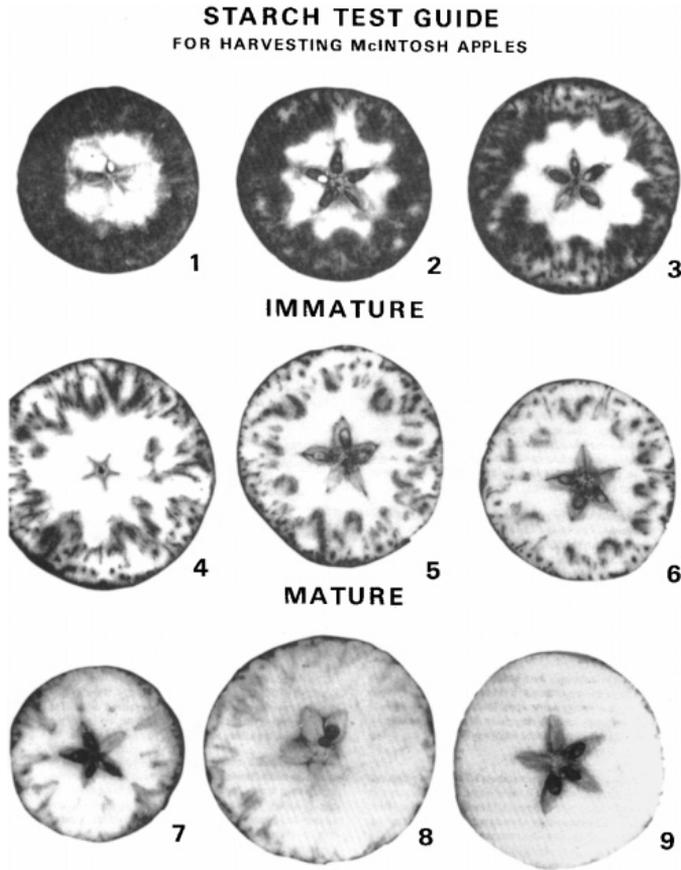


Figure 3.5. Starch test scale for red delicious apples. (Source: [31])

Moisture-Content Measurement

In addition to electrical measurement, moisture content can be determined accurately by oven drying, to establish the dry weight after removal of moisture.

Biological Destructive Testers

The presence of pathogens and bacteria can be determined by a range of cell-culture techniques. Samples of skin or tissue are placed in a suitable growth media and incubated for several days. Pathogens reproduce to levels at which they can easily be detected and counted.

Combinations of Test Methods

For many crops one measurement of maturity or quality is inadequate. Attempts have been made to combine several measurements into a maturity index. For apples, the Streif index is defined as

$$SI = F/(RS) \quad (3.4)$$

where F is the penetrometer firmness force in Newtons divided by 9.8 measured with an 11 mm probe pushed to a depth of 8 mm in 2 seconds, R is the Brix refractive index (% Brix), and S is the starch-conversion stage, measured on a scale from 1 to 10 [32, 33]. Typical values for apples at harvest are in the range from (on average) 0.07 for the Jonagold cultivar to 0.3 for Elstar [33]. Use of this index enabled the optimum harvest date (OHD) to be predicted in one cultivar of apple (Jonagold) using the following formula:

$$\text{Days to OHD} = -47.7 - 19.6 \cdot \text{Ln}(SI) \quad (3.5)$$

The formula was not reliable for individual orchards to an accuracy of better than a few days but did predict the optimum harvest date for a district well [34].

3.1.4 Nondestructive Testing Methods and Their Advantages

Nondestructive methods offer significant advantages over destructive methods. Obviously there is a saving in the number of fruits or vegetables wasted, but there are other advantages: First, the same fruit can be retested several times throughout its lifetime, giving a reduction in variability as a result of random sampling of fruit in growth and storage trials (each fruit becomes its own control). This means that test procedures should become more reliable and rigorous, because measurements can be correlated better with fruit performance by tracking the development and storage behavior of individual fruit. This improves predictions of storage life. Other advantages are that samples taken from packed fruit do not need to be replaced. This has major advantages for quality-control inspection procedures: There is no mess or problem of disposal of sampled fruit—they can be repacked or returned to the packing line. On-line assessment of every fruit is a possibility. In scientific experiments, because the same fruit can be used again and again without interrupting its normal life cycle, the number of samples required can be reduced.

Tests that could be conducted in situ in the orchard have additional advantages. It would be possible to test fruit during growth, without removal from the tree, and to evaluate the relationship between orchard management and postharvest properties in a rigorous fashion.

The following tests are in principle nondestructive, although in some cases a test may result in damage. For example, mechanical test pressures may exceed tissue failure strength in some samples, especially as the fruit softens. Care should be taken to ensure that the test is not producing any effect that would be harmful in the long term. Pitts *et al.* [35] tested several nondestructive devices on apples but found problems with all of them. Abbott *et al.* [36] recently produced a detailed review.

Mechanical NDT Tests

Mass and Bulk Density

Mass is one of the most obvious quality indices and is easy to measure. Density can be measured using Archimedes' principle. The fruit is weighed in air and then suspended in water. The apparent loss in mass is equal to the volume of the fruit multiplied by the density of water. Computer-linked scales can perform the simple calculations automatically and shorten measurement times to a few seconds. Flotation systems can

sort fruit and vegetables whose specific gravity is close to 1.0 (e.g., mangoes). Addition of salt or sugar solutions to the water tank can alter the density and hence the cut-off point between floating and sinking fruits. Bubbling air through water reduces the effective density, and this also can be used for sorting.

Quasistatic Low-pressure Indenters

A large number of different techniques involve applying low-pressure compression to intact fruits and vegetables. Some are quasistatic, and in general these can be set up using a modern texture analyser. For example, Jeffery and Banks [37] described a kiwifruit indenter in which a modified micrometer dial gauge applied a fixed weight to a specimen placed underneath. The weight caused the sample to deform, and from the shape of the deformation curve a softness index was established by appropriate curve-fitting techniques. This procedure was relatively slow and required a computer logging system. A similar approach has been taken in a commercial meter for testing avocados. In this case the load was applied using a weight hung at the end of a pivoted beam, with a dial gauge at the other end. Similar see-saw-type loading devices have been used by several researchers [36].

For leafy vegetables such as lettuce and cabbage it is possible to assess the harvest maturity by lightly pressing the vegetable by hand. French workers have used a texture analyzer for this purpose [16].

Dynamic Low-pressure Indenters

Others indenters involve impact devices using small accelerometers to measure impact parameters. In the Soft-sense system (Hortresearch, Hamilton, NZ), kiwifruit are dropped from a small height onto a force transducer [38]. The Kiwifirm (Industrial Research Ltd., Auckland) applies a small impact load to the sample without producing apparent damage [38]. Several other research groups have developed testing devices, and all claim advantages for their systems [14, 16, 39–43]. Typical analyses involve measurement of the dwell time (the period that the impact force remains above 50% or 80% of the peak value), or the area under the force–time curve (see Section 3.3).

Nondestructive Use of Texture Analyzers

Some researchers have used modern texture analyzers capable of following complex loading patterns. Provided the equipment is sufficiently sensitive and is capable of measuring force and displacement continuously, a wide range of nondestructive measurements can be taken. Measurements made include compressibility, energy absorption during a loading cycle, and whole-fruit modulus of elasticity determined by compression between flat platters. This latter test is suited to cherries and other soft fruits [16].

Acoustic Methods

Clark and Mikelson [44] described the acoustic-response method, for an estimate of the overall or global texture of fruits that are approximately spherical. The acoustic impulse response method makes use of the sound signal emitted by the fruit as it vibrates in response to a gentle short-duration shock, produced by tapping with a small rod or pendulum. The signal is captured by a microphone, and the principle frequency of

vibration is then calculated by means of a fast Fourier transform. The technique has been applied successfully to the determination of melon ripeness. In other products, problems of interpreting the data remain.

In principle, the resonant frequency of an object depends directly on its geometry, its mass, and the modulus of elasticity of the material of which it is made. In the case of fruit, the modulus of elasticity reduces as the fruit matures (from 5 MPa for an unripe green apple to 0.5 MPa for an overripe fruit), and this reduction may indicate changes in the turgor pressure and physical properties of the plant tissue [45, 46].

Cooke and Rand [47, 48] proposed a mathematical model for the interpretation of the vibrational behavior of intact fruit. They showed that the elastic modulus (or Young's modulus) can be estimated satisfactorily as follows:

$$E = C \cdot f^2 \cdot m^{2/3} \cdot \rho^{1/3} \quad (3.6)$$

where E is the coefficient of elasticity (Pa), C is a constant, f is the frequency with greatest amplitude (Hz), m is the mass (kg), and ρ is the density (kg/m^3). The implications of this are that E can be determined provided two other parameters (density and mass) are known. For a particular cultivar density variation is often quite small. Mass can be measured in the laboratory, and in the field it can be estimated from fruit diameter.

Other laboratory techniques also have been suggested for measuring the vibrational characteristics of fruits and vegetables. The resonance method suggested by Abbott *et al.* [49, 50] involves placing the whole fruit on a platform that can be vibrated over a range of frequencies from 20 to 4000 Hz, and measuring the response using an accelerometer. The random-vibration method [51] makes use of excitation over a wide range of frequencies. Resonant properties are deduced from the transmitted vibration across the fruit for certain preselected frequencies. Problems remain, including the need to allow for fruit shape variability. Sonic tomography and vibration transmission also have been studied [24, 52].

Visual Nondestructive Measurements

Size and Shape

As fruits grow their shapes and sizes change. Assessment of size is one of the simplest methods for assessing maturity prior to and at harvest for many vegetables. In some cases the size determines the product: Capsicums may be marketed as zucchini while small, and as marrows when large. Baby corns, sweet corn, and maize may be the same cultivar (*Zea mays saccharata*) harvested at different stages. Mango maturity can be assessed in some cultivars by examining the position and angle the shoulder makes with the stalk and its point of attachment to the fruit [23].

Color

Surface color is used widely for maturity and quality assessment and is probably the most common characteristic used in the selection and harvesting of many fruit. Generally assessments are still performed manually, particularly in the field, although inside packing sheds color sorters are now available commercially for many crops. Although manual measurement may be subject to operator fatigue, human error, and variability, automatic

systems are still often considerably inferior, because humans provide a more subjective assessments than machines. Color assessment often can be complex: For example, in apples that develop a partial red color, harvest maturity is based on the background color, which remains in the green-to-yellow range of colors, even though the red color appears to dominate. Human graders have been shown to fail to grade fruit correctly due to the influence of the blush color [53].

Machine vision systems are likely to continue to advance rapidly in speed and accuracy and should become increasingly reliable for discrimination of fruit maturity. However, in some countries the social implications and the cost of automation may be unacceptable. Although automatic systems using image analysis are being introduced worldwide, currently the majority of fruits and vegetables still are assessed by humans, because cost considerations and the availability of labor still favour human operators. The efficiency and effectiveness of manual inspection remain crucial. Ergonomic factors affect the performance of people [24], and so studies are in progress into what factors affect the ability of people to detect substandard products. Studies of background color and lighting levels are aimed at optimizing the physical environment [54, 55]. Other issues, such as ensuring that production processes do not harm the environment or offend human ethical values, also must be considered [13].

Lighting levels are particularly important in grading operations. High levels of illumination are recommended for most grading using natural or artificial lighting. Lux levels should be high (in excess of 1000) [56], but it is also important to avoid glare and strong reflections from background tables and rollers. Black backgrounds maximize the relative light levels on the fruit being inspected, but if the light is directly overhead, and the operator is looking at the fruit from the side, then the lower part of the fruit may be too dark. For this reason non-white neutral colors (grays) are probably the most useful inspection backgrounds.

In storage, visual appearance is often a good indicator of changes in product quality. Random sampling and inspection for rots, shrivel, and decay are used widely to monitor long-term product quality.

Near-infrared Reflectance and Other Electromagnetic Radiation

Researchers have studied the use electromagnetic radiation from ultraviolet to infrared [57]. As well as measuring moisture content, near-infrared reflectance measurements have been correlated with quality factors such as sugar content, firmness, carbohydrates, and acidity in various fruits including apples and mangoes [42, 58, 59]. Near-infrared reflectance also has been used to detect bruising in apples [60, 61].

Gamma- and x-rays also have been used to detect internal disorders in fruit and vegetables [23]. Radiographic systems have detected water core in apples, hollow heart in potatoes, split pits in peaches, and the maturity of lettuce heads at harvest [62, 63].

Delayed Light Emission and Transmittance

Some fruit will re-emit radiation for a short time after exposure to a bright light. The amount of delayed radiation is a measure of the chlorophyll present, and this is inversely dependent on the maturity. The method has been used with satumas, tomatoes, and papaya. Other studies have used the transmittance and reflectance of light for papaya and citrus [23]. The reradiated energy is affected by wavelength and intensity of the

exciting radiation, sample thickness, area of excitation, and ambient temperature, and there is considerable variation among similar samples [64].

Other Visual Methods of Assessment

A wide number of visual indicators can be used to determine maturity and quality. The state of foliage is particularly useful for many vegetable crops (e.g., optimum storage of potatoes may be obtained if they are dug up after the leaves and stems have died down).

Nondestructive Testing—Electrical and Nuclear Magnetic Resonance

Very little success has been achieved in using electrical properties of fruit and vegetables for nondestructive assessment of quality. However, there is some evidence that electrical conductivity is affected by mechanical or physiological damage [23, 65].

Nuclear magnetic resonance has shown some potential as a method for detecting internal defects in apples, peaches, pears, onions, prunes, and olives. It also can be used to determine sugar content in bananas [66], potatoes, grapes, and carrots [52], and oil content in avocados [67]. Magnetic resonance imaging can provide a three-dimensional image and has been used to detect defects in apples and other fruits [68]. Nuclear magnetic resonance and magnetic resonance imaging are expensive techniques.

Nondestructive Testing—Chemical

Respiration Rate

As discussed in Section 3.2, some fruits and vegetables change their rate of respiration as they mature and ripen. These changes can be used to identify when fruit and vegetables are near the end of their storage life and should be sold.

Head Gases and Aroma

Ripeness of fruit can be indicated by changes in the production of ethylene, or other volatiles. Although these changes may be too small for humans to detect, fruit flies and other insects may be attracted by volatiles. Monitoring sensors therefore also could be used.

Nondestructive Testing—Biological

Harvest dates can be estimated from the elapsed time after flowering for some fruits and vegetables. In practice it is difficult to be precise. Degree-day calculations (cumulative product of time and temperature) are a guide to maturity for some greenhouse crops.

Biosensors

Biosensors that mimic taste and smell offer useful potential for quality assessment [24]. These include ion-selective glass electrodes. These have enzyme or antibody film coverings that affect the number of hydrogen ions sensed. Metal-oxide gas detectors can react to specific gases. These detectors are still in the experimental stage.

Problems with Nondestructive Test Methods

There are a number of problems that need to be overcome before the benefits of nondestructive testing can be exploited. Nondestructive methods are relatively new, and in most cases the results of the measurement have yet to be interpreted in terms that are relevant to the industry. These methods are generally indirect, in the sense that they

measure properties that may be a consequence of quality, but correlations between these properties and practical terms are not known.

Industry and researchers are familiar with current assessment measures, and although they recognize the inadequacy of most of the tests, they are reluctant to adopt new measurements until they are proven to be of value and well related to more familiar measures. This implies that before a new system is implemented, there is a need for full-scale trials including taste-panel assessments, conducted over a number of seasons.

The problem is always to correlate the reading from the device with an appropriate quality parameter such as bruising resistance or texture determined by taste panels. In general the correlations for most devices have been quite poor [35]. However, better results have been obtained when more than one parameter has been measured, and correlations determined using a statistical treatment (such as principle component analysis) or an expert system approach [69]. Nondestructive testing methods therefore offer some exciting possibilities for improving quality assessment but may be slow to gain industrial acceptance. New methods, however, are being developed continually.

3.1.5 Maintenance of Quality

In the fresh fruit and vegetable market, meeting a standard requires that appropriate quality-assurance methods be in place to govern the production and postharvest handling of the product. In order to maintain these standards it is essential that an appropriate quality-assurance program is established. In this regard the ISO 9000 series of standards is a major aid in helping producers to establish their own procedures [5, 6]. However, these standards are not designed for food crops in particular. Rather they are guidelines to setting and operating standards, rather than quality standards themselves. For every crop it is helpful if clear standards are defined, as this gives producers clear indications of what is needed. Such standards tend to be large documents. They can be developed by producers or by marketing and retail organizations.

International and Domestic Markets

Standards for export crops can be particularly demanding, especially where crops may compete with locally grown products. However, more frequently the standards accurately reflect consumer expectations in the market. On local and domestic markets standards are sometimes nonexistent, although this depends on the size of the country and the level of infrastructure. In either case there is an economic advantage in producing crops of a recognizable standard: commercial buyers prefer products from growers with good reputations for quality who therefore obtain a greater return [8, 9, 14, 24]. There are marketing advantages in using a brand name that carries a quality assurance for the customer.

Standards may be established that relate to all aspects of production and supply of a fruit or vegetable. For all of the criteria listed in Table 3.3 standards may be set that range from total absence of certain defects to a maximum tolerance level. Any standard should be clear and easy to understand for graders. Illustrations and color photographs are often more useful than written explanations. An example of a domestic market standard is shown in Table 3.8. Criteria used in U.S. standards for fruits and vegetables are given in the Appendix, Table 3. A1.

Table 3.8. Product specifications for oranges

Characteristic			
Cleanliness	Free from dirt, dust, or other foreign substances (except wax)		
Shape	Typical of variety (slight variation allowed)		
Washing	All graded oranges to be washed and waxed		
Sizing	Less than 15% variation in diameter in any one container		
Acceptable packaging types	F40 packs (18 kg), cartons (16–20 kg), bins (300 kg), plastic bags (various)		
	Grade 1	Grade 2	Grade 3
Color (navel oranges)	Full color	Full color	< 10% surface greening on < 25% of batch
Color (valencia oranges)	Full color	< 10% surface greening on < 25% of batch	< 20% surface greening on < 50% of batch
Sizing	65–90 mm diameter	55–90 mm diameter	55–90 mm diameter
Skin thickness	< 8 mm	Variable thickness OK	Variable thickness OK
Stems—Length	< 3.0 mm	< 3.0 mm	< 10% over 3.0 mm
—missing buttons	Nil	< 20%	< 50%
Defect allowances			
Light blemish	< 1.0 cm ²	< 3.0 cm ²	Light blemish OK
Dark blemish (oleocellosis)	None	< 0.5 cm ² aggregate (each fruit)	< 3.0 cm ² aggregate (each fruit)
Bruises, cuts, and punctures	None	< 0.25 cm ² aggregate length	< 1.0 cm ³ aggregate length
Insect damage /stains	None	< 0.5 cm ²	< 1 cm ²
Rots and decay	None	< 2%	< 5%
Dry fruit	None	Nil	< 5%

Adapted from Turners and Growers (New Zealand) TAG Quality System.

In the example in Table 3.8 there are three grade standards, and fruit are labeled according to the grade. This example is a fairly simple standard, representing an attempt to develop a completely new standard for the market. There are no requirements for prior cool storage, temperature of product, different grade sizes, labeling, or spray-deposit limits, although these may be required in other documentation. Growers are expected to supply produce to the market sorted to meet these grade standards.

Quality Inspection and Control

In order to meet these standards fruits and vegetables must be inspected prior to submission to market, and substandard produce must be downgraded or removed. Quality control requires continual checks to ensure that standards are maintained, by sampling graded produce carefully. In apple-handling systems this is achieved by sampling 1 carton in 50 or 100 in each grade size, according to a specified protocol. Accurate records should be kept of all defects found in these results, so that slow changes in quality levels can be identified and corrected. If an out-of-grade carton is found, immediate corrective action is needed. Usually this is achieved by advising sorters of the problem and by repacking cartons packed since the last sample was checked. Some specifications require that a second carton be checked immediately and corrective action taken according to the

cumulative results of the two samples. Again it is important that the procedure be well understood and rigorously enforced.

This level of control requires good training of graders and inspectors. Inspectors may be employed by the packing shed or by a marketing organization. Incentives to graders for maintaining good quality are needed, rather than threats, which are usually counterproductive.

Total Quality Management

In order to develop and maintain quality systems in the postharvest industry, total quality management procedures offer a basis for successful management development. The emphasis of this system is to aim at continual improvement in quality standards within the organization. This is achieved by a process of identifying small changes that would improve product quality, implementing the changes, evaluating the outcomes, and then adapting or modifying further. Total quality management requires that quality definitions are discussed and agreed by everyone in the production chain, and that a quality manual is produced for use by the company concerned.

In the apple and kiwifruit industries in New Zealand, quality standards are maintained by a process in which approved grading sheds employ quality-assurance personnel, who are trained to conduct regular checks on produce, using a carefully developed sampling procedure [70]. Checks also are conducted by the main marketing organization on receipt of product at the shipping depot. Strict documentation procedures are implemented throughout. The marketing organization conducts training and certification programs for quality-control personnel each year, including updating staff on changes to standards.

Quality checks are required throughout the postharvest chain. These include not only checks on the quality of the product but also an assessment of the procedures and facilities at each part of the handling chain. Checks on product quality normally are undertaken whenever the product changes hands or has completed a unit operation in the chain.

Changes in Standards

Standards should be variable in time rather than absolute, in order to enable producers to react to, or be proactive in setting, new consumer requirements. This implies that the technologist has to continually seek new measurement methods capable of establishing new standards at all points in the product's life.

References

1. Salunkhe, D. K., and S. S. Kadam. 1995. *Handbook of Fruit Science and Technology*. New York: Dekker.
2. FAO. 1995. Commodity Review and Outlook 1994–5. *FAO Economic and Social Development Series No. 53*. Rome: Author.
3. FAO. 1996. FAO Yearbook 1995. *FAO Statistics Series No. 132*. Rome: Author.
4. MaCrae, R., R. K. Robinson, and M. J. Sadler eds. 1993. *Encyclopedia of Food Science, Food Technology, and Nutrition*. London: Academic Press.
5. ISO. 1986. *ISO 8402: Quality—Vocabulary*. International Standards Organisation.
6. ISO. 1987. *ISO 9000-9003: Quality Management Systems*. International Standards Organisation.

7. Kader, A. A. 1983. Postharvest quality maintenance of fruits and vegetables in developing countries. In *Postharvest Physiology and Crop Production*, pp. 455–470. New York: Plenum.
8. Holt, J. E., and D. Schoorl. 1984. A hard systems approach to the management of quality in apple distribution. *Agricultural Systems* 13:129–142.
9. Herregods, M. 1994. Profitable quality: Cost and profits concerning marketing a product preferred by the consumer. In *COST 94, the Postharvest Treatment of Fruit and Vegetables, Quality Criteria*, 5th Workshop Proceedings, Slovenia 1994, pp. 21–32. Luxembourg: European Commission.
10. Kader, A. A. 1997. Quality in relation to marketability of fruits and vegetables. Keynote paper, Proceedings of the 5th Fruit Nut and Vegetable Engineering Symposium, University of California, Davis.
11. Kader, A. A. 1992. *Postharvest technology of agricultural crops*. Publication 3311, 2nd ed. University of California, Davis.
12. Dauthy, M. E. 1995. Fruit and vegetable processing. *FAO Agricultural Services Bulletin* ASB 119. Rome: FAO.
13. Amos, N. D., L. U. Opara, C. J. Studman, G. L. Wall, and C. Walsh. 1994. Techniques to assist with meeting international standards for the export of fresh produce. Section 6a, XII CIGR AgEng'94 Conference, Milan, Italy.
14. Watada, A. 1993. The methodology for the determination of the quality of fruits and vegetables: Influence of new technologies. Paper 37, International Symposium on the Quality of Fruit and Vegetables: Influence of Pre- and Post-harvest Factors and Technology, International Society for Horticultural Science, Chania, Greece.
15. Abbott, J. A., A. E. Watada, and D. R. Massie. 1976. Effe-Gi, Magness-Taylor, and Instron Fruit pressure testing devices for apples, peaches and nectarines. *Journal of the American Society of Horticultural Science* 101:698–700.
16. Duprat, F., E. Pietri, M. G. Grotte, and C. J. Studman. 1995. A multipurpose firmness tester for fruits and vegetables. *J. Computers and Electronics in Agriculture* 12:211–223.
17. Bourne, M. C. 1979. Theory and application of the puncture test in food texture measurement. In *Food Texture and Rheology*, ed. P. Sherman, pp. 95–142. New York: Academic Press.
18. Harker, F. R., R. J. Redgwell, I. C. Hallett, S. H. Murray, and Carter, G. 1997. Texture of fresh fruit. *Horticultural Reviews* 20:121–224.
19. Harker, F. R., J. H. Maindonald, and P. J. Jackson. 1996. Penetrometer measurement of apple and kiwifruit firmness: Operator and instrument differences. *J. American Society of Horticultural Science* 121:927–936.
20. Bourne, M. C. 1966. Measurement of shear and compression components of puncture tests. *J. Food Science* 31:282–291.
21. Yang, Y. M., and N. N. Mohsenin. 1974. Analysis of the mechanics of the fruit pressure tester. *J. Texture Studies* 5:213–238.
22. Knight, C. 1991. Crop production harvesting and storage. In *Vegetable Processing*, ed. D. Arthey and C. Dennis, pp. 12–41. New York: Blackie.

23. Thompson, A. K. 1996. *Postharvest Technology of Fruit and Vegetables*. Oxford: Blackwell.
24. Shewfelt, R. L., and S. E. Prussia. 1993. *Postharvest Handling: A Systems Approach*. San Diego: Academic Press.
25. Kapsalis, J. G. 1987. *Objective methods in food quality assessment*. Boca Raton, FL: CRC Press.
26. Studman, C. J., and L. Boyd. 1994. Measurement of firmness in fruits and vegetables. XII CIGR World Congress AgEng '94 Conference, Milan, Italy.
27. Griessel, H. M. 1995. The use of internal and positional variations in flesh firmness of "May Glo" nectarines as a maturity determinant. *J. South African Society of Horticultural Science* 5 (2):81–84
28. Ha, N. G., L. U. Opara, and C. J. Studman, 1997. Effect of harvest dates, storage temperature, and postharvest treatments on quality of Buoi Mango fruit. *6th Agricultural Engineering Students Conference Proceedings*, Massey University, pp. 68–71.
29. Mohsenin, N. N. 1986. *Physical Properties of Plant and Animal Materials*, 2nd ed. New York: Gordon and Breach.
30. Nelson, S. O., W. R. Forbus, and K. C. Lawrence, 1995. Microwave dielectric properties of fruits and vegetables and possible use for maturity sensing. Conference Proceedings, *International Conference on Harvest and Postharvest Technologies for Fresh Fruits and Vegetables*, Mexico, pp. 497–504.
31. Priest, K. L., and E. C. Lougheed. 1988. Evaluating maturity of McIntosh and Red Delicious apples. *Agdex 211/50*. Ontario, Canada: Ontario Ministry of Agriculture and Food.
32. Streif, J. 1983. Der optimale Erntetermin beim Apfel: I. (Optimum harvest date for apples: I. Quality and maturity). *Qualitätsentwicklung und Reife. Gartenbauwissenschaft* 48: p154–159.
33. Streif, J. 1996. Optimum harvest date for different apple cultivars in the Bodensee area. COST 94, Determination and Prediction of Optimum Harvest Date of Apple and Pears. Working Group Proceedings, Norway, 1994, pp. 15–20. Luxembourg: European Commission.
34. de Jager, A., and F. P. M. M. Roelofs. 1996 Prediction of optimum harvest date of Jonagold. COST 94, Determination and Prediction of Optimum Harvest Date of Apple and Pears. Working Group Proceedings, Norway 1994, pp. 21–32. Luxembourg: European Commission.
35. Pitts, M., R. Cavaliere, S. Drake, and J. Fellman. 1997. Evaluating apple firmness sensors. *Washington State University Tree Fruit Postharvest Journal* 8(4):13–22.
36. Abbott, J. A., R. Lu, B. L. Upchurch, and R. L. Stroshine, 1997. Technologies for nondestructive quality evaluation of fruits and vegetables. *Horticultural Reviews* 20:1–120.
37. Jeffery, P. B., and N. H. Banks, 1994. Firmness-temperature coefficient of kiwifruit. *New Zealand Journal of Crop and Horticultural Science* 22:1–4.
38. Hopkirk, G., A. White, M. S. Arnold, and J. H. Maindonald, 1994. Four new devices for measuring kiwifruit firmness. KMB Project Report 92/16. Auckland, New Zealand: New Zealand Kiwifruit Marketing Board.

39. Delwiche, M. J., N. Singh, H. Arevalo, and J. Mehlschau, 1991. A second generation fruit firmness sorter. ASAE Paper 91-6042. St Joseph; MI: ASAE.
40. Peleg, K. 1994. A new sensor for non-destructive measurement of fruit firmness. *Conference Proceedings, 5th International Conference on the Physical Properties of Agricultural Materials*, University of Bonn, Bonn, 1993, paper 931136.
41. Bellon, V., G. Rabatel, and C. Guizard. 1992. Automatic sorting of fruit: Sensors for the future. *Food Control* (January):49–54.
42. Chen, P., and Z. Sun, 1991. A review of non-destructive methods for quality evaluation and sorting of agricultural products. *Journal of Agricultural Engineering Research*, 49:85–98.
43. Ruiz-Altisent, M. 1994. Non-destructive quality measurement and modelling in fruits. *Conference proceedings, 5th International Conference on the Physical Properties of Agricultural Materials*, University of Bonn, Bonn, 1993, paper 931153.
44. Clarke, H. L., and W. Mikelson. 1942. Fruit ripeness tester. U.S. patent 2277037.
45. Duprat, F., M. G. Grotte, E. Pietri, and D. Loonis. 1997. The acoustic response method for measuring the overall firmness on fruit. *Journal of Agricultural Engineering Research* 66:251–259.
46. De Baerdemaeker, J. 1989. The use of mechanical resonance measurements to determine fruit texture. *Acta Horticulturae* 258:331–339.
47. Cooke, J. R. 1972. An interpretation of the resonant behavior of intact fruits and vegetables. *Transactions of the American Society of Agricultural Engineers* 16:1075–1080.
48. Cooke, J. R., and R. H. Rand. 1973. A mathematical study of resonance in intact fruits and vegetables using a 3-media elastic sphere model. *Journal of Agricultural Engineering Research* 18:141–157.
49. Abbott, J. A., G. S. Bachman, R. F. Childers, J. V. Fitzgerald, and F. J. Matusik. 1968. Sonic techniques for measuring texture of fruits and vegetables. *Food Technology* 22:101–112.
50. Abbott, J. A., R. F. Childers, G. S. Bachman, J. V. Fitzgerald, and F. J. Matusik. 1968. Acoustic vibration for detecting textural quality of apples. *Proceedings of the American Society for Horticultural Science* 93:725–737.
51. Finney, E. E. 1971. Random vibration techniques for non-destructive evaluation of peach firmness. *Journal of Agricultural Engineering Research* 16:81–87.
52. Tollner E. W., J. K. Brecht, and B. L. Upchurch. 1993. Nondestructive evaluation: Detection of external and internal attributes frequently associated with quality or damage. In *Postharvest Handling: A Systems Approach*, ed. R. L. Shewfelt and S. E. Prussia, pp. 225–255. San Diego: Academic Press.
53. Paulus, I., and E. Schrevens. 1997. A methodology to study the interaction of external features of apples on human quality classification. Conference Proceedings, Fifth International Symposium on Fruit, Nut and Vegetable Production, University of California, Davis.
54. Guyer, D., R. Brook, and E. Timm, 1993. Lighting systems for fruit and vegetable sorting. Bulletin AEIS-618, USDA. East Lansing, MI: Michigan State University.

55. Studman, C. J. 1994. Design of apple grading tables. Project report, New Zealand Apple and Pear Marketing Board, Wellington, New Zealand.
56. Nicholas, J. V. 1985. Color and light for the inspection table. Sirtec Publication no. 1. Wellington, New Zealand: Department of Scientific and Industrial Research.
57. Birth G. S., and G. H. Hecht, 1987. The physics of near infrared reflectance. In *Near Infrared Technology in the Agricultural and Food Industries*, ed. P. C. Williams and K. H. Norris, pp. 1–15. St. Paul, MN: Society of Cereal Chemists.
58. Kouno, Y., T. Mizuno, and H. Maeda. 1993. Feasibility study into NIR techniques for measurement of internal qualities of some tropical fruits. *Proceedings of ICAMPE '93*, Korean Society for Agricultural Machinery, Seoul, pp. 326–333.
59. Birth, G. S., G. G. Dull., W. P. Renfro, and S. J. Kays. 1985. Nondestructive spectrophotometric determination of dry matter in onions. *J. Amer. Soc. Hort. Sci.* 110:297–303.
60. Upchurch, B. L., H. A. Affeldt, W. R. Hruschka, K. H. Norris, and J. A. Throop. 1990. Spectrophotometric study of bruises on whole “Red Delicious” apples. *Transactions of the American Society of Agricultural Engineers* 33:585–589.
61. Affeldt, H. A., B. L. Upchurch, K. H. Norris, and J. A. Throop. 1989. Bruise detection on “Golden Delicious” apples. *American Society of Agricultural Engineers* 89–3011. St Joseph, MI: ASAE.
62. Cavalieri, R. 1997. Detection of watercore in apples. *Washington State University Tree Fruit Postharvest Journal* 8(4):3–8.
63. Lenker, D. H., and P. A. Adrian, 1971. Use of X-rays for selecting mature lettuce heads. *Transactions of the American Society of Agricultural Engineers* 4:894–898.
64. Gunasekaran, S. 1990. Delayed light emission as a means of quality evaluation of fruits and vegetables. *CRC Critical Reviews in Food Science and Nutrition* 29 (1):19–34.
65. Koto, K. 1987. Non-destructive measurements of fruit quality by electrical impedance. *Agricultural Machinery Research Report no. 17*, Kyoto University, Japan.
66. Cho, S. I., and G. W. Krutz, 1989. Fruit ripeness detection by using NMR. *American Society of Agricultural Engineers Paper* 89–6620. St Joseph, MI: ASAE.
67. McCarthy, M. J., P. Chen, R. Kauten, and Y. Sarig, 1989. Maturity evaluation of avocados by NMR methods. *American Society of Agricultural Engineers technical paper* 89–3548.
68. Chen P., M. J. McCarthy, and R. Kauten, 1989. NMR for internal quality evaluation of fruits and vegetables. *Transactions of the American Society of Agricultural Engineers* 32:1747–1753.
69. Steinmetz, V., E. Mesbahi, V. Bellon-Maurel, E. Molto, and R. Pons, 1997. Flexible real-time sensor fusion for peach quality assessment. *Conference Proceedings, Fifth International Symposium on Fruit, Nut and Vegetable Production*, University of California, Davis.
70. Enzafruit International. 1997. *Quality Assurance Manual*. Hastings, New Zealand: Enzafruit.

3.2 Fruit and Vegetable Storage Requirements

E. W. Hewett

3.2.1 Fundamentals

It is becoming increasingly important to present top-quality products to discerning international consumers. Most major supermarket chains buy horticultural products to specification (size, weight, color, and freedom from defects); buyers are rejecting products that deviate from precontracted specification ranges.

It is therefore imperative that growers, exporters, shippers, and scientists work together to ensure that customer quality standards are being met. An important first step in this process is to ensure that all concerned understand the nature of product perishability and appreciate important biological factors that influence deterioration.

An understanding of these features will improve industry's ability to deliver high-quality produce to its markets, both locally and overseas. Postharvest technologies need to take account of the living nature of horticultural products, and in particular their susceptibility to physical, pathological, and physiological deterioration. Both physical and temperature abuse of produce can lead to increased decay. Optimum storage temperatures are generally as close to freezing temperature as can be achieved without inducing chilling injury. For some crops this is 0°C, but for crops sensitive to chilling it may be as high as 16°C. Optimized refrigeration and controlled-atmosphere storage conditions reduce respiration, achieving slower deterioration and enhanced storage life. Preventing ethylene contamination of the storage environment from external sources or by ethylene-producing crops is important to maximize storage life. These approaches, combined with new engineering and molecular approaches, will be important in the production and handling systems used to get products to market.

Postharvest technologists attempt to maintain quality through the cool chain, slowing deterioration to improve storage and shelf life, and thus ensuring consumers have high-quality fruits and vegetables to purchase. They seek to control the handling, transport, and storage conditions to ensure optimal quality [1]. Postharvest physiologists seek to understand and develop strategies to control the basic physiological and biochemical changes that occur in harvested plant products during handling and storage. It is only through such understanding that sensible and meaningful recommendations can be made for manipulation of elements in the cool chain to ensure quality products reach all markets.

Morphological structure of fruits and vegetables is incredibly diverse, comprising all plant parts, such as roots, underground stems, stems, leaves and flowers, and flower parts [2]. Therefore it is not surprising that handling and storage recommendations for maximum postharvest life vary from product to product.

This section addresses several key elements that influence deterioration in freshly harvested horticultural crops. It also indicates potential opportunities for quality enhancement, based on recent biological discoveries.

3.2.2 Horticultural Products Are Living Entities

The harvesting operation is a catastrophic event, removing the product from its source of minerals and water (from roots) and in most cases from its source of energy

(carbohydrates from the leaves). Freshly harvested horticultural products remain alive after harvest, in contrast with other food products such as cereals, meat, and milk-based items. Horticultural products are very active metabolically, as reflected in their relatively high respiration rate.

After harvest, horticultural products do not remain in a constant condition but continue to develop through the following processes that are genetically predetermined:

maturation \Rightarrow ripening \Rightarrow senescence \Rightarrow death

The developmental processes of maturation and ripeness merge and overlap. Maturity may have two aspects, and it is important to distinguish between them. *Physiological maturity* refers to that stage of development when maximum growth has occurred and proper completion of subsequent ripening can occur even if the product has been harvested. *Commercial maturity* is that stage of development of a fruit or vegetable that is required by the market (retailer or consumer); it may have little relation to physiological maturity and may occur at various stages of ripeness depending on individual consumer preference [3].

Final eating quality is critically dependent on harvesting at the correct maturity stage, so that normal ripening can occur with the concomitant development of flavor, texture, aroma and juiciness required by consumers. In many fruits, ripening occurs either on or off the tree. Optimum eating quality for many vegetable crops is attained before full maturity. Examples include peas, green beans, broccoli, sweet corn, zucchini, asparagus, and leafy vegetables; if these products are left attached to the parent plant and not harvested at the correct time, their quality is much reduced. A range of maturity indices has been developed for fruits and vegetables (see Table 3.5).

Deterioration commences at harvest; postharvest technologies are designed to slow the rate of ripening and senescence and hence quality decline. If deterioration is rapid, poor-quality product can be removed at the point of production or packing at which quality inspection occurs; if deterioration is slow the product may pass initial quality inspection yet be of reduced acceptability to consumers because of poor appearance, texture, or taste. This is likely to make future purchases unlikely [2].

3.2.3 Deterioration of Fresh Products

Deterioration results from three main types of effects: physical, physiological, and pathological. Most of the following discussion involves physiological effects, but a brief mention of physical and pathological effects is warranted.

Physical Effects

Produce can sustain mechanical or physical damage at all stages of the chain from harvest to consumption. Bruises, cuts, abrasions, and fractures occur as a result of poor handling or inadequate packaging. Such damage dramatically increases water loss and susceptibility to infection by postharvest fungi and bacteria. In addition, respiration and ethylene production are enhanced in wounded tissue; these all lead to rapid quality loss in physically damaged organs.

Both product firmness and water status influence susceptibility to mechanical damage. Development of gentle yet effective handling systems and appropriate packages, together

with education of personnel, are required to minimize physical damage. This is discussed in Section 3.3.

Pathological Effects

Postharvest decay of produce results in major losses of horticulture foods worldwide. Any physical damage to produce provides an ideal entry point for such pathogens.

A wide range of fungi and bacteria contribute to postharvest losses in fruit and vegetables throughout the world, especially in situations in which cool-chain management is inadequate. These postharvest pathogens may infect produce at various preharvest stages through plant or fruit development, at harvest, or after harvest while products are in store or in transit to market.

Latent infections occur during flower or early fruit development, but after initial penetration the infective agent becomes quiescent until the product has reached a stage of maturity or ripeness that allows it to recommence growth and spread throughout the product. Examples include *Botrytis cinerea* on strawberries, *Monolinia fruticola* on peaches, and *Colletotrichum gloeosporioides* on avocado and mango. Removal of previously infected fruit and application of appropriate fungicides at bloom are the recommended means of control.

Infection through wounds in the product surface (including the picking scar in fruit such as kiwifruit) occur especially following mechanical damage sustained through rough handling at harvest and during grading, sizing, and packaging. Saprophytic organisms that would normally not cause a problem, such as *Rhizopus stolonifera* and *Mucor* spp., have the potential to cause substantial damage, in addition to other ubiquitous fungi and bacteria. Introduction of systems to minimize risks of physical damage, such as training of staff and total quality management systems, should reduce opportunities for this type of infection to occur.

Growth of many postharvest fungi is inhibited or markedly reduced at storage temperatures below 5°C. Unfortunately several successful pathogens, including *Botrytis cinerea* and *Monolinia fruticola*, survive and grow slowly at 0°C, ready to proliferate rapidly when product temperature increases after storage.

Although many pathogens have the potential to cause postharvest decay, most losses are the result of a relatively few highly effective organisms, many of which have a wide host range, attacking tropical, subtropical, and temperate products (Table 3.9). Traditionally control has required a range of chemicals, applied both as preharvest sprays and postharvest dips or drenches, but increasingly markets are not accepting such postharvest treatments.

Recent consumer resistance to spray residues has led to development of nonchemical or biological control methods to combat postharvest fungal pathogens. Naturally occurring yeasts seem promising for reducing several widespread postharvest pathogens [5].

Chilling Injury

Most tropical and subtropical products are susceptible to chilling injury when exposed to temperatures above freezing but below a critical threshold temperature for each particular product (Fig. 3.6 and Table 3.10). These chilling temperatures cause breakdown

Table 3.9. Some major postharvest diseases of fresh fruits and vegetables

Crop	Disease	Pathogens
Apple, pear	Lenticel rot	<i>Phylocataena vagabunda</i> (<i>Gloeosporium album</i>)
	Blue mold rot	<i>Penicillium expansum</i>
	Bull's eye rot	<i>Pezizula malicorticis</i>
	Bitter rot	<i>Colletotrichum gloeosporioides</i>
Stone fruits	Eye rot	<i>Nectria galligena</i>
	Brown rot	<i>Monolinia fructicola</i>
	Grey mold	<i>Botrytis cinerea</i>
	Rhizopus	<i>Rhizopus</i> spp.
Strawberries	Blue mold	<i>Penicillium expansum</i>
	Alternaria rot	<i>Alternaria alternata</i>
	Gray mold rot	<i>Botrytis cinerea</i>
	Rhizopus rot	<i>Rhizopus</i> spp.
Grapes	Anthraco nose	<i>Colletotrichum gloeosporioides</i>
	Gray mold rot	<i>Botrytis cinerea</i>
	Alternaria rot	<i>Alternaria alternata</i>
	Cladosporium rot	<i>Cladosporium herbarum</i>
Banana and plantain	Blue mold rot	<i>Penicillium expansum</i>
	Anthraco nose	<i>Colletotrichum musae</i>
	Thielaviopsis finger-stem rot	<i>Thielaviopsis paradoxa</i>
	Botryodiplodia finger-stem rot	<i>Botryodiplodia theobromae</i>
Tropical fruits	Fusarium finger-stem and spot rot	<i>Fusarium roseum</i>
	Cigar-end rot	<i>Verticillium theobromae</i>
	Crown rot	<i>Fusarium roseum</i>
Pineapple	Thielaviopsis soft rot: water blister, black rot	<i>Thielaviopsis paradoxa</i>
	Bacterial brown rot	<i>Erwinia ananas</i>
Tomatoes	Fruitlet core rot	<i>Penicillium funiculosum</i>
	Alternaria rot	<i>Alternaria alternata</i>
	Buckeye rot	<i>Phytophthora parasitica</i>
	Botrytis rot	<i>Botrytis cinerea</i>
Carrots	Rhizopus rot	<i>Rhizopus</i> spp.
	Sour rot	<i>Geotrichum candidum</i>
	Bacterial soft rot	<i>Erwinia carotovora</i>
	White rot	<i>Sclerotinia minor</i>
Citrus fruits	Black mold	<i>Thielaviopsis basicola</i>
	Blue mold rot	<i>Penicillium italicum</i>
	Green mold rot	<i>Penicillium digitatum</i>
	Brown rot	<i>Phytophthora citrophthora</i>
	Diplodia rot	<i>Diplodia natalensis</i>
	Phomopsis rot	<i>Phomopsis citri</i>
	Alternaria rot	<i>Alternaria citri</i>
Avocado	Trichoderma rot	<i>Trichoderma lignorum</i>
	Sour rot	<i>Geotrichum candidum</i>
	Dothiorella stem-end rot	<i>Dothiorella gregaria</i>
	Diplodia stem-end rot	<i>Diplodia natalensis</i>
Kiwifruit	Anthraco nose	<i>Colletotrichum gloeosporioides</i>
	Phomopsis stem-end rot	<i>Phomopsis citri</i>
	Gray mold	<i>Botrytis cinerea</i>
	Surface mold	<i>Alternaria alternata</i>

(Cont.)

Table 3.9. (Continued)

Crop	Disease	Pathogens
Papaya	Anthracnose	<i>Colletotrichum gloeosporioides</i>
	Rhizopus rot	<i>Rhizopus</i> spp.
	Alternaria rot	<i>Alternaria alternata</i>
	Crater rot	<i>Rhizoctonia carotae</i>
	Botrytis rot	<i>Botrytis cinerea</i>
Lettuce	Bacterial soft rot	<i>Erwinia carotovora</i>
Onions	Neck rot	<i>Botrytis</i> spp.
	Bacterial soft rot	<i>Erwinia carotovora</i>
	Smudge	<i>Colletotrichum circinans</i>
	Basal and/or bulb rot	<i>Fusarium</i> spp.
Potatoes	Late blight	<i>Phytophthora infestans</i>
	Dry rot	<i>Fusarium solani</i>
	Black scurf	<i>Rhizoctonia solani</i>
	Pink rot	<i>Phytophthora erythroseptica</i>
	Sweet potatoes	Rhizopus rot
Beans	Fusarium rot	<i>Fusarium oxysporum</i>
	White rot	<i>Sclerotinia minor</i>
	Botrytis rot	<i>Botrytis cinerea</i>
	Anthracrose	<i>Colletotrichum lindemuthianum</i>

Source: [4].

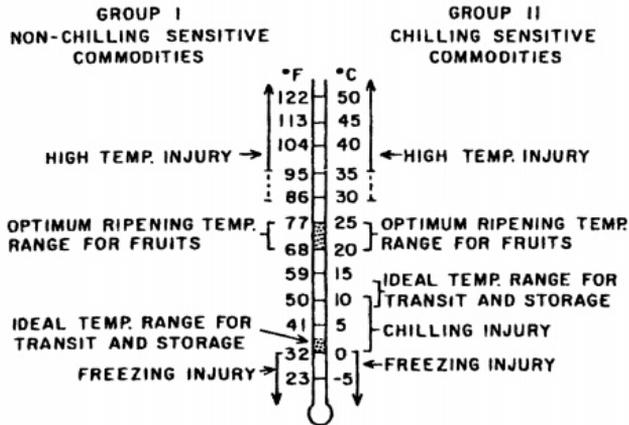


Figure 3.6. Temperature effects on chilling-sensitive and nonsensitive crops. (Source: [21])

Table 3.10. Fruits and vegetables classified according to sensitivity to chilling injury

Group I: Not Sensitive to Chilling		Group II: Sensitive to Chilling	
Fruit	Vegetables	Fruit	Vegetables
Apple	Artichokes	Avocados	Beans, snap
Apricot	Asparagus	Bananas	Cassava
Blackberry	Beans, Lima	Breadfruit	Cucumbers
Blueberries	Beets	Carambola	Eggplant
Cherries	Broccoli	Cherimoya	Ginger
Currants	Brussels sprouts	Citrus	Muskmelon
Dates	Cabbage	Cranberry	Okra
Figs	Carrots	Durian	Peppers
Grapes	Cauliflower	Feijoa	Potatoes
Kiwifruit	Celery	Guavas	Pumpkins
Loquats	Corn, sweet	Jackfruit	Squash
Nectarines ^a	Endive	Jujubes	Sweet potatoes
Peaches ^a	Garlic	Longan	Taro
Pears	Lettuce	Lychees	Tomatoes
Persimmon ^a	Mushrooms	Mangoes	Watermelon
Plums ^a	Onions	Mangosteen	Yams
Prunes	Parsley	Olives	
Raspberry	Parsnips	Papayas	
Strawberry	Peas	Passion fruit	
	Radishes	Pepinos	
	Spinach	Pineapples	
	Turnips	Plantain	
		Pomegranate	
		Prickly pear	
		Rambutan	
		Sapodilla	
		Sapota	
		Tamarillo	

Source: [21].

^a Some cultivars are sensitive to chilling.

of cellular membranes, resulting in loss of compartmentalization within the cells of the tissue, increased leakiness, water soaking of tissue, and eventually pitting or browning. Some chilled fruit fail to ripen normally, while in others there is an accelerated rate of senescence and a shortened shelf life. Symptoms of chilling injury are varied and depend on the product but include surface pitting, surface browning, internal browning to vascular tissue or in parenchyma cells, water soaking, and mealiness or wooliness of texture (Table 3.11).

The ultimate symptom of severely chilled products is decay; the original cause of such rotten produce may not be realized unless the temperature history of the product is known.

Chilling injury is avoided by storing susceptible products above their threshold damage temperatures, although reduction of injury can be achieved by exposing products to

Table 3.11. Characteristics of chilling for specific fruits

Product	Approximate Lowest Safe Storage Temperature (°C)	Typical Symptoms
Apple	0–3	Internal browning (breakdown)
Avocado	5–12 ^a	Pitting, browning of pulp and vascular strands
Beans (snap)	7	Water soaking, rots
Banana	12	Brown streaking on skin
Cucumber	7	Dark color, water-soaked areas
Egg plant	7	Surface scald
Lemon	10	Pitting of flavedo, membrane staining, red blotches
Lime	7	Pitting
Mango	5–12 ^a	Dull skin, brown areas
Melon	7–10 ^a	Pitting, surface rots
Papaya	7	Pitting, water-soaked areas, rots
Peach	0–5	Mealiness, browning near stone
Peppers	7	Water soaking, rots
Pineapple	6–12 ^a	Brown or black flesh
Sweet potato	12	Flesh discoloration, breakdown, rots
Tomato	10–12	Pitting, water soaking, rots

Source: [2].

^a Temperature range indicates variability among cultivars of their susceptibility to chilling injury.

preconditioning or intermittent temperatures or to high temperatures (38–45°C) prior to low-temperature storage [6–8].

3.2.4 Physiological Factors Involved in Deterioration

Respiration

All living things respire to generate energy for continued metabolism. A simplified summary equation for respiration is



Respiration is highly temperature dependent (Fig. 3.7). The lower the temperature (down to 0°C) of harvested fruit and vegetables the lower the respiration rate. Consequences of lowering respiration rate include

- Reduction in carbohydrate loss
- Decreased rate of deterioration
- Increased storage and shelf life

Low-temperature storage (given cognizance of potential chilling injury in susceptible products) is the major weapon that the postharvest operator has to maintain quality and extend life of harvested products (Fig. 3.8). Low temperatures not only reduce respiration rate, but also reduce

- Water loss through transpiration
- Nutritional loss

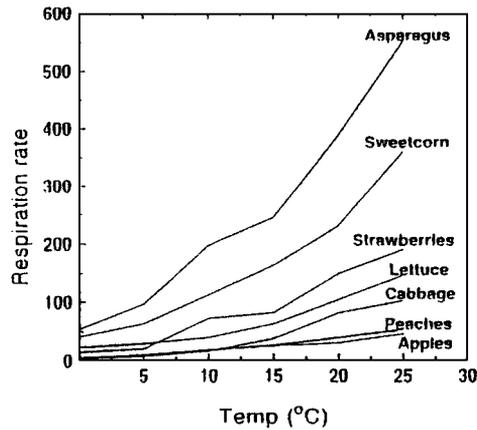


Figure 3.7. Temperature effects on respiration of several fresh horticultural products. (modified from [9])

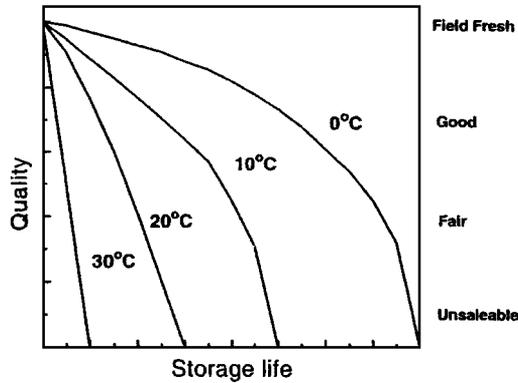


Figure 3.8. Generalized temperature effects on quality and storage life of horticultural products. (modified from [9])

- Postharvest decay
- Ethylene production

Practical application of such information has been incorporated into successful cool-chain management for many products. Immediately after harvest, products should be placed in a well-ventilated shade environment to prevent large temperature increases that occur if products are exposed to direct sunlight.

Rapid cooling as soon as possible after harvest (to reduce respiration rate) is used commonly in the horticultural industry, particularly for very perishable products such as strawberries and broccoli but also for kiwifruit and apples. Hydrocooling, vacuum

cooling, or forced air-cooling is used widely to remove field heat rapidly. The method chosen depends on the crop.

Respiration rate of horticultural products varies, but as a general rule perishability is a function of respiration rate; the greater the respiration rate the more perishable the product and the shorter the time it can be stored and still maintain acceptable quality. Actively growing products, such as asparagus or broccoli, or tropical fruit, such as cherimoya or mango, have high rates of respiration and limited storage life.

Differences do exist among cultivars, so it is important that this be taken into account for cool store and packaging. A summary of optimum storage temperatures for selected fruits and vegetables is shown in the Appendix, Table 3.A3.

Packages should be designed to allow cool air to flow directly over products, ensuring rapid temperature pull-down and consequent temperature maintenance. Regrettably, too many packages in current use are largely impenetrable to air movement, resulting in a slow temperature decrease, influencing quality negatively (see Section 3.3).

Minimizing temperature variation from the optimum recommended during storage improves uniformity in product quality. Refinements are being made in refrigeration-control systems, cool-store design, and pallet-stacking patterns to optimize air temperature and airflow through and around pallets in cool stores [10]. This prevents hot spots from developing in localized areas within the store that would lead to higher respiration rates, more rapid deterioration, and hence poorer quality than in parts of the store in which product temperature was optimised (see Section 3.4).

Freezing point of most horticultural products after harvest is between -2 and -1°C . Temperatures in coolstores should be maintained at or slightly above 0°C for temperate products to avoid freezing; damage caused by freezing will disrupt cell walls and membranes, leading to loss of cellular compartmentation and increased susceptibility to infection by fungi and bacteria. Deterioration is rapid, generally irreversible, and terminal if products are removed from freezing temperatures and allowed to thaw.

Increasing interest is being shown in the potential of short-term prestorage exposure to relatively high temperatures (35 – 55°C) as a means of reducing chilling injury [7], as a quarantine treatment for disinfesting products of pests [11] and for reducing the rate of some senescence processes. Product-specific high-temperature treatments have been shown to reduce ethylene production, prevent yellowing and retard softening in a number of products [6], all of which can extend storage life.

Controlled and Modified Atmospheres

It has long been recognised (since the 1920s and 1930s) that controlling the atmosphere around products influences respiration rate. Respiration rate is a function of O_2 and CO_2 concentration. Respiration decreases as O_2 concentration in the environment, and hence inside the product, is reduced. Eventually an O_2 concentration is reached, below which CO_2 production rapidly increases (Fig. 3.9) as anaerobic respiration predominates. The O_2 concentration at which respiration is at a minimum is called the *anaerobic compensation point* (ACP). The ACP or lower oxygen limit [13] varies with temperature, fruit type, and cultivar and among fruit, probably because of varying skin permeance to O_2 and CO_2 movement [14]. Derivation of ACP needs to be undertaken for

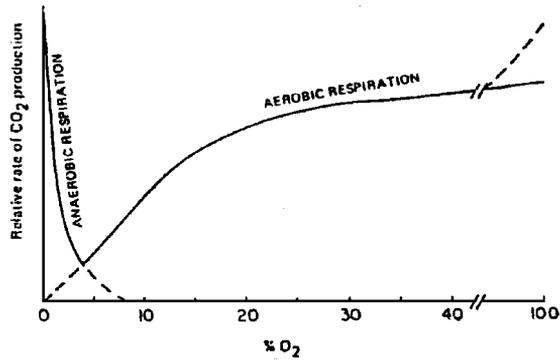


Figure 3.9. A schematic representation of the effects of O_2 concentration of aerobic and anaerobic respiration rates of fresh vegetables. (Source: [12])

intact and minimally processed products destined for controlled-atmosphere or modified-atmosphere storage. Development of atmospheres with O_2 lower than the ACP inevitably leads to off flavors and loss of quality. Knowledge of ACPs for crops allows optimization of controlled-atmosphere conditions for different products and avoids problems such as development of off flavor and physiological damage that may result from anaerobic respiration and subsequent fermentation processes at suboptimal O_2 atmospheres.

Controlled-atmosphere storage has been the mainstay of the European and North American apple industries for many decades but has not been commercially successful for many horticultural crops. Adoption of this technology has been slow in other countries, although information on desired atmospheres for a range of crops is available [15–20]. This technology must be seen as an adjunct to good temperature management [21].

Generally controlled-atmosphere stores operate with $0^\circ C$ atmosphere containing 1% to 5% CO_2 and 1% to 3% O_2 , depending on crop and cultivar [15–20].

Recent improvements of gas and temperature control systems have allowed cool-store operators to refine these ranges; for some cultivars of apple, 0% CO_2 and 1.0% O_2 are being used. The lower the O_2 concentration, and the higher the CO_2 concentration, the higher the risk of problems arising, generally manifested as some form of external or internal product browning.

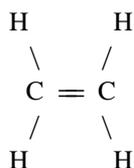
Modified atmospheres, in which the atmosphere is passively regulated depending on product mass, temperature, and nature of a polymeric film package, are being used increasingly for minimally processed or “fresh-cut” products [22]. In addition, they can be used to reduce disorders in whole fruit [23]. A major problem with modified-atmosphere generation in polymeric films arises from the fact that the increase in product respiration rate with temperature is greater than the increase in film permeability to respiratory gases over the same temperature range. This results in elevated CO_2 and depressed O_2 concentrations inside packs that may exceed the physiological thresholds for damage, leading to development of off-flavor. It is crucial that temperatures of modified-atmosphere packages are prevented from rising too high.

Development of models that predict the physiological responses of products to irregular and often unpredictable changes in temperature during handling, storage, and transport of modified-atmosphere packaged products should assist in the development of relatively low-risk systems [24].

Ethylene

Ethylene is an ubiquitous, naturally occurring gaseous compound produced by plants that at very low concentrations can influence many aspects of plant growth and development [25]. It is particularly important in the maturation, ripening and senescence of fruits, flowers and vegetables.

Ethylene is a simple, two-carbon unsaturated compound:



It is also a contamination product from petroleum-powered engines, from cigarette smoke, and from the ballasts of fluorescent lights.

Ethylene can have both positive and negative effects on product quality [21]. Positive effects include

- Coordination of several ripening events
- Induction of abscission and color change from green to yellow
- Induction of softening, juice development, and flavor
- Promotion of uniform ripening
- Commercial ripening of avocados, bananas, kiwifruit, and tomatoes

However, important negative effects of ethylene on quality include

- Accelerated senescence even at low temperatures
- Induced loss of green color in leaves
- Induction of abscission in flowers and fruit
- Increased organ softening even at concentrations as low as $0.001 \mu\text{L} \cdot \text{L}^{-1}$ [26].
- Induction of some physiological disorders
- Initiation of ripening in climacteric fruit that cannot be reversed.

Increasingly, attempts are being made to prevent ethylene from accumulating in packages or in cool stores. Ethylene-absorbing material can be placed inside sachets (e.g., potassium permanganate on perlite) or is used for scrubbing ethylene from cool stores (e.g., activated charcoal). However, in general, stringent attention to hygiene conditions in and around packing sheds and ensuring that exhaust fumes do not contaminate products are the best ways of preventing ethylene accumulation.

Fruits can be categorized as climacteric or nonclimacteric (Table 3.12) depending on their response to and ability to produce ethylene [27]. Climacteric fruit are those that produce relatively large amounts of ethylene during ripening on or off the tree. Peak production generally coincides with a concurrent respiratory peak within 3 to 10 days of harvest, after which respiration may decline. Ethylene production is autocatalytic in that

Table 3.12. Fruits classified according to respiratory behavior during ripening

Climacteric	Nonclimacteric
Apple	Blackberry
Apricot	Cacao
Avocado	Carambola
Banana	Cashew apple
Biriba	Cherry
Blueberry	Cucumber
Breadfruit	Date
Cherimoya	Eggplant
Durian	Grape
Feijoa	Grapefruit
Fig	Jujube
Guava	Lemon
Jackfruit	Lime
Kiwifruit	Longan
Mango	Loquat
Muskmelon	Lychee
Nectarine	Okra
Papaya	Olive
Passion fruit	Orange
Peach	Peas
Pear	Pepper
Persimmon	Pineapple
Plantain	Pomegranate
Plum	Prickly pear
Quince	Raspberry
Rambutan	Strawberry
Sapodilla	Summer squash
Sapote	Tamarillo
Soursop	Tangerine
Tomato	Mandarin
	Watermelon

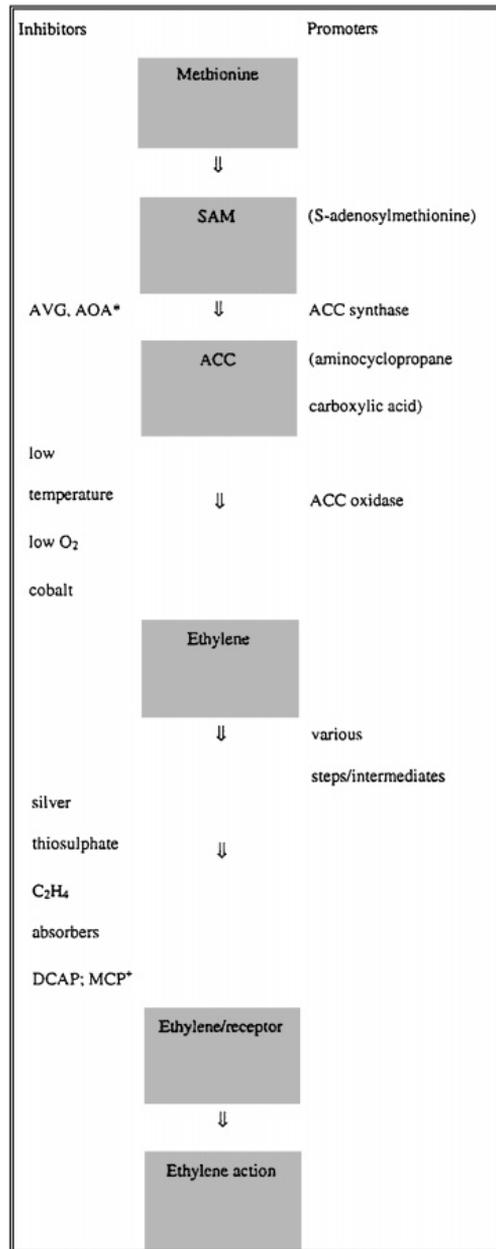
Source: [21].

production will continue, stimulated by endogenous levels, even if an external source is removed.

Nonclimacteric fruit do not produce either a respiratory peak or an ethylene surge during ripening, and there is no autocatalytic ethylene production. Rather they show a steady decline in respiration rate and a low rate of ethylene production as ripening proceeds. They normally are ready to eat at harvest. Exposure to ethylene, or an analogue of ethylene, stimulates ethylene production, but only as long as the source is present.

These behavioral patterns have implications for storage, particularly with regard to mixed loads. Ethylene-sensitive products should not be stored with climacteric fruit otherwise premature, unplanned, and uncontrolled ripening can occur (see Section 3.4).

Ethylene in plants is synthesized from the amino acid methionine through the pathway involving aminocyclopropane carboxylic acid (ACC, Fig. 3.10). Two key enzymes



*AVG - aminoethoxyvinylglycine; AOA – amino oxyacetic acid
 *DCAP-diazocyclopentadiene; MCP- 1-methylcyclopropene

Figure 3.10. Ethylene biosynthetic pathway in plants including process inhibitors and promoters.

catalyze reactions in this pathway: ACC synthase, the rate-limiting enzyme that converts S-adenosylmethionine to ACC; and ACC oxidase, which converts ACC to ethylene.

Storage of climacteric fruit at low temperatures or low O₂ concentrations results in reduced ethylene production because of the inhibition of ACC oxidase activity. Thus another beneficial effect of low temperature controlled-atmosphere storage of climacteric fruit is this reduction in endogenous ethylene, which in turn helps extend storage and shelf life. However, the beneficial effects of controlled-atmosphere are enhanced if a scrubber is utilized to maintain ethylene concentrations at a minimum.

The pathway of ethylene biosynthesis is well established for higher plants (see Fig. 3.10). Some chemicals are available to inhibit the key rate-limiting enzyme, ACC synthase, but although relatively effective in reducing ethylene production, they have not gained commercial acceptance. Low temperatures and controlled-atmosphere conditions reduce the conversion of ACC to ethylene. Several compounds are available that when absorbed into the plant or product can prevent ethylene from binding to putative ethylene receptors and hence inhibit ethylene action [25]. Silver thiosulphate is widely used in the cut-flower industry to prolong shelf life [25]. New compounds such as diazocyclopentadiene and 1-methylcyclopropene are very effective inhibitors of ethylene action [28] and are still under evaluation for use in the cut-flower and nursery industries.

Ethylene is widely used on several fruit crops to induce uniform and consistent ripening, to provide “ready to eat” product for consumers. Application of ethylene as a ripening or degreening gas, at concentrations from 10 to 200 ppm, generally combined with CO₂ or N₂, is used routinely for tomatoes, bananas, avocados, kiwifruit, and citrus at temperatures of 15 to 25°C and at 80% to 95% relative humidity [2].

3.2.5 Preharvest Factors Affecting Postharvest Quality

Ultimate eating quality of fruit is largely predetermined at harvest. Choice of cultivar, rootstock, irrigation, fertilizer regime, training, and pruning systems will impact fruit size and color at harvest.

Calcium is the fifth most abundant element in soil, and symptoms of Ca deficiency are rarely seen on leaves of plants. However, because uptake, transport, and distribution of Ca within plants is different from those of other major elements, fruit, bulky leafy vegetables, and root crops are often deficient in this element. More than 30 physiological quality defects can be directly attributed to shortage of Ca [29]. Disorders caused by deficiencies in Ca often develop during cool storage, with fruit having appeared in good condition at harvest.

Uptake of calcium is predominantly by young, actively growing roots; this element moves passively with water in xylem tissues at a rate largely determined by transpiration. It does not move in phloem tissues to any great extent and hence is not redistributed from one organ to another. Calcium is distributed mainly to those tissues with a high transpiration rate, so organs with a large surface area-to-mass ratio (leaves, young developing fruit) will contain more calcium than those with a lesser surface area-to-mass ratio (large fruit, tubers, heart vegetables). This element plays a crucial role in maintaining integrity of cell walls and membranes. It is also involved in transduction of external

stimuli to cells. Thus, deficiencies of calcium dramatically affect quality attributes such as firmness, texture, and susceptibility to a range of physiological disorders such as pitting, internal breakdown and chilling injury, as well as influencing susceptibility to infection by postharvest pathogens [29–31].

Calcium enhancement is best achieved by adding Ca directly to fruit, either by pre-harvest sprays or postharvest vacuum infiltration or dipping treatments using CaCl_2 [32]. Application of Ca to the soil as lime generally will not ameliorate Ca-related fruit-quality problems. It should be possible to establish product-specific calcium threshold concentrations, below which quality problems are likely to occur, and devise appropriate management strategies to enhance tissue concentrations of calcium.

Other mineral elements can affect product quality. Excess of nitrogen, imbalance of nitrogen, potassium and magnesium, and deficiency of phosphorus and certain microelements all can result in detrimental effects on product quality and reduce storage life.

3.2.6 Harvesting and Its Effect on Postharvest Quality

Great care must be taken during harvesting of perishable fruits and vegetables to avoid physical damage (see Section 3.3). Any mechanical damage that occurs at harvest, during movement of product to the packhouse, or through grading and packing lines will result in enhanced respiration, elevated ethylene production, water loss and increased susceptibility to infection by postharvest pathogens, all of which can induce rapid deterioration and loss of quality. A number of simple but effective steps can be taken to reduce physical damage from occurring during this phase of the harvesting and handling system [33]. These include careful handling of the product at all stages of the operation, good sanitation and hygiene with all equipment (this may include addition of chlorine [as hypochlorite at 50–150 ppm] to water dumps in the packing and grading line to reduce microorganisms), maintenance of packing equipment to prevent excessive drops onto hard surfaces, and padding of all machinery surfaces on which products may impact.

Curing is a simple method of reducing losses due to decay and water loss during storage of some products including some citrus fruit, root, tuber, and bulb crops. Prestorage exposure for 1 to 10 days (time depending on product), at 12 to 20°C for potatoes, kiwifruit, and citrus, or to 30 to 40°C for sweet potatoes, yams, onions, garlic, and cassava, allows some moisture loss but induces wound healing by development of new suberized epidermal tissue, thus preventing decay development and further excessive water loss [21].

3.2.7 New Postharvest Opportunities

Customers, especially supermarket buyers, are requiring increasingly uniform and consistent products with narrowing margins of quality specification. Technologists are poised to make further significant contributions to improving the quality of fresh harvested horticultural products. Further refinements can be expected as we learn more about the interaction of preharvest factors with responses of products to the postharvest environment.

Specific knowledge of product response to endogenous CO₂, O₂, and C₂H₄ at different times and temperatures after harvest, together with the sophisticated temperature- and gas-control systems currently available, creates the opportunity for modulating storage environments to continuously minimize respiration rate and hence deterioration. This can be achieved in both static land-based cool stores and in seagoing containers. Intermittent shock treatments to minimize some physiological disorders, including chilling injury, also may be possible [7].

Considerable efforts are being made to develop active packaging to overcome problems associated with changing temperatures during storage and transit of modified-atmosphere packages. Development of films that can increase permeability in response to a chemical signal (e.g., ethanol or acetaldehyde produced during anaerobic respiration) may soon become a reality. The possibility for creating surface coatings, which reduce water loss but at the same time allow the establishment of appropriate internal atmospheres in fruit but do not allow physiologically “dangerous” levels of gases to develop, is exciting.

Rapid advances are being made in creating equipment that can monitor internal quality attributes nondestructively. Already it is possible to grade fruit electronically for size and colour; near infrared detectors already are used commercially in Japan and France to measure soluble solids content in fruit on grading lines. The ability to separate products accurately and consistently on the basis of specific internal chemical composition creates the opportunity for providing particular quality attributes (taste or sensory) for discerning niche markets.

Genetic manipulation of plants probably offers the greatest opportunity for making long-term sustainable advances in reducing deterioration rates and extending storage and shelf life of horticultural products. Naturally occurring, long-life mutant tomatoes are now available for commercial production. Combining genetic traits conferring normal shape and flavor attributes with those conferring reduced ethylene production, traditional plant breeders have been able to create highly acceptable cultivars that have a much extended shelf life compared with previous cultivars.

Molecular biology has allowed scientists to incorporate desirable genes into the genetic makeup of traditional crops. The first commercially produced food plant of this type accepted by the FDA in the USA was the Flavr Savr tomato produced by Calgene. Molecular technology was used to inhibit cell-wall breakdown and hence slow fruit softening. The Flavr Savr tomatoes are more resistant to handling damage, and hence postharvest decay, than normal tomatoes, as well as producing a more viscous paste that is a great advantage for tomato processors. Tomatoes have been produced with much-reduced ethylene production and hence greatly extended shelf life. Similar lines have been created for apple, peach, and kiwifruit and are being evaluated for other production and quality attributes.

References

1. Shewfelt, R. L., and S. E. Prussia, ed. 1993. *Postharvest Handling: A Systems Approach*. Academic Press, San Diego, California, USA.

2. Wills, R. H. B., T. H. Lee, D. Graham, W. B. McGlasson, and E. G. Hall. 1989. *Postharvest: An Introduction to the Physiology and Handling of Fruit and Vegetables*. N.S.W. University Press, Sydney, Australia.
3. Watada, A. E., R. C. Herner, A. A. Kader, R. J. Romani, and G. L. Staby. 1984. Terminology for the description of developmental stages of horticultural crops. *HortSci.* 19:20–21.
4. Somme, N. F., J. Fortlag, and D. C. Edwards. 1991. Postharvest diseases of selected commodities. In *Postharvest Technology of Horticultural Crops*, ed. A. A. Kader, University of California Publication 3311, pp. 117–160.
5. Wilson, C. L., M. E. Wisniewski, ed. 1994. *Biological Control of Postharvest Diseases of Fruits and Vegetables: Theory and Practice*. CRC Press, Boca Raton, Florida, USA.
6. Klein, J. D., and S. Lurie. 1992. Heat treatments for improved postharvest quality of horticultural crops. *Hort. Technology* 2:316–320.
7. Wang, C. Y. 1993. Approaches to reduce chilling injury of fruits and vegetables. *Hort. Rev.* 15:63–95.
8. Woolf, A. B., and M. Lay Yee. 1997. Pretreatment at 38°C of Hass avocado confers thermotolerance to 50°C hot water treatments. *HortSci.* 32:705–708.
9. Hardenburg, R. E., A. E. Watada, and C. Y. Wang. 1986. The commercial storage of fruits, vegetables, and florist and nursery stocks. U.S. Department of Agriculture, Agriculture Handbook 66, pp. 136.
10. Amos, N., D. J. Cleland, N. H. Banks, and A. C. Cleland. 1993. A survey of air flow, temperature and relative humidity patterns on a large horticultural coolstore. *Refrigeration Sci. Tech.* 3:414–422.
11. Paull, R. E. 1994. Heat and cold treatments. In *Insect Pests and Fresh Horticultural Products: Treatment and Responses*, ed. R. E. Paull and J. W. Armstrong, pp. 191–222. UK: CAB International.
12. Kader, A. 1987. Respiration and gas exchange of vegetables. In *Postharvest Physiology of Vegetables*, ed. J. Weichmann, pp. 25–43. Marcel Dekker, New York, USA.
13. Yearsley, C. W., N. H. Banks, S. Ganesh, and D. J. Cleland. 1996. Determination of lower oxygen limits for apple fruit. *Postharvest Biol. Tech.* 8:95–109.
14. Dadzie, B. K., N. H. Banks, D. J. Cleland, and E. W. Hewett. 1996. Changes in respiration and ethylene production of apples in response to internal and external oxygen partial pressures. *Postharvest Biol. Tech.* 9:297–309.
15. Kupferman, E. 1997. Controlled atmosphere storage of apples. In *CA'97, vol. 2, Apples and Pears*, ed., E. J. Mitcham, pp. 1–30. Proceedings of the 7th International Controlled Atmosphere Research Conference, University of California, Davis, Postharvest Horticultural Series No. 16.
16. Richardson, D. G. 1997. Controlled atmosphere storage of pears. In *CA '97, vol. 2, Apples and Pears*, ed., E. J. Mitcham, pp. 1–30. Proceedings of the 7th International Controlled Atmosphere Research Conference, University of California, Davis, Postharvest Horticultural Series No. 16.
17. Kader, A. A. 1997. A summary of CA requirements and recommendations for fruits other than apples and pears. In *CA '97, vol. 3, Fruits Other than Apples and Pears*, ed.,

- A. A. Kader, pp. 1–34. Proceedings of the 7th International Controlled Atmosphere Research Conference, University of California, Davis, Postharvest Horticultural Series No. 17.
18. Saltveit, M. E. 1997. A summary of CA requirements and recommendations for harvested vegetables. In *CA '97, vol. 4, Vegetables and Ornamentals*, ed., M. E. Saltveit, pp. 98–117. Proceedings of 7th International Controlled Atmosphere Research Conference, University of California, Davis, Postharvest Horticultural Series No. 18.
 19. Reid, M. S. 1997. A summary of CA requirements and recommendations for ornamentals and cut flowers. In *CA '97, vol. 4, Vegetables and Ornamentals*, ed. M. E. Saltveit, pp. 98–117. Proceedings of the 7th International Controlled Atmosphere Research Conference, University of California, Davis, Postharvest Horticultural Series No. 18.
 20. Gorny, J. R. 1997. A summary of CA requirements and recommendations for fresh-cut (minimally processed) fruits and vegetables. In *CA '97, vol. 5, Fresh-cut Fruits and Vegetables and MAP*, ed. J. R. Gorny, pp. 30–66. Proceedings of the 7th International Controlled Atmosphere Research Conference, University of California, Davis, Postharvest Horticultural Series No. 19.
 21. Kader, A. A. 1992. Postharvest technology of horticultural crops. University of California, Publication 3311, pp. 296.
 22. Watada, A. E., N. P. Ko., and D. A. Minott. 1996. Factors affecting quality of fresh-cut horticultural products. *Postharvest Biol. Tech.* 9:115–125.
 23. Hewett, E. W., and C. J. Thompson. 1989. Modified atmosphere storage and bitter pit reduction in Cox's Orange Pippin apples. *Sci. Hortic.* 39:117–139.
 24. Merts, I., D. J. Cleland, N. H. Banks, and A. C. Cleland. 1993. Prediction of chilling times for objectives of regular multi-dimensional shape using a general geometric factor. *Refrig. Sci. Technol.* 33:259–267.
 25. Abeles, F. B., P. W. Morgan, and M. Saltveit. 1992. *Ethylene in Plant Biology*. Academic Press, San Diego, California, USA.
 26. Jeffrey P. B., and N. H. Banks. 1996. Effects of ethylene on kiwifruit softening in coolstore. *N. Z. Kiwifruit Journal* 110 (March): 9.
 27. Biale, J. B., and R. E. Young. 1981. Respiration and ripening in fruit: Retrospect and prospects. In *Recent Advances: Biochemistry of Fruits and Vegetables*, ed., J. Friend and M. J. Rhodes, pp. 1–39, Academic Press, New York, USA.
 28. Serek, M., E. C. Sisler, and M. S. Reid. 1994. Novel gaseous ethylene binding inhibitor prevents ethylene effects in potted flowering plants. *J. Am. Soc. HortSci.* 119:1230–1233.
 29. Shear, C. B. 1975. Calcium related disorders of fruits and vegetables. *HortSci.* 10:361–365.
 30. Conway, W. S. 1989. Altering nutritional factors after harvest to enhance resistance to postharvest disease. *Phytopath.* 79:1384–1387.
 31. Poovaiah, B. W., G. M. Glenn, and A. S. N. Reddy. 1988. Calcium and fruit softening. *Hort. Rev.* 10:107–153.

32. Hewett, E. W., and C. B. Watkins. 1991. Bitter pit control by sprays and vacuum infiltration of calcium in "Cox's Orange Pippin" apples. *HortSci.* 26:284–286.
33. Kader, A. A. 1993. Postharvest handling. In *The Biology of Horticulture*, ed. J. E. Preece and P. E. Read, pp. 353–377. John Wiley and Sons, New York, USA.

3.3 Handling Systems and Packaging

C. J. Studman

3.3.1 Postharvest Losses

Fruit and vegetables must be transferred from the field to the table, to arrive in a state that is acceptable to the consumer. Although traditional farm- and orchard-gate sales still can provide a useful income, the increasingly lucrative demand for year-round supplies from urban dwellers and international markets requires that there has to be an increasing level of handling, transportation, and storage of products. Unlike cereals, fruit and vegetables are essentially highly perishable commodities. Most fruit and vegetable crops begin to deteriorate as soon as they are harvested, and most are particularly prone to handling damage at all times. In general, the level of susceptibility of these products to handling damage is greatly underestimated, usually because the effects of mishandling do not appear until some time after the damage occurred.

Estimates of postharvest losses are difficult to make. Generally accepted values are 25% to 50% of production in less-developed countries [1–4], and around 10% to 25% elsewhere. Poor handling and storage can easily result in a total crop loss anywhere. Estimated losses for various crops in less-developed countries are given in Table 3.13. In developed marketing systems losses are lower (e.g., Table 3.14). As the table implies, not all losses are due to poor handling, but handling damage is known to accelerate other types of deterioration, particularly the development of molds and rots.

This section reviews postharvest procedures and operations for fresh fruit and vegetables and considers ways to avoid handling damage. Packaging options also are described. Requirements for fruit intended for canning and processing are generally less severe, but financial returns are also usually lower.

3.3.2 Postharvest Operations

The types of operations are summarized in Table 3.15. Clearly processes differ among crops, and some crops do not require all the stages listed or may require further operations to enhance the quality of the product. Seven major steps are involved, and the example given in the right-hand column is based on the postharvest chain for apples. Other crops are discussed in the text.

Harvest

Product for the fresh-fruit market mostly is harvested by hand into suitable containers. Fruit are easily damaged at harvest time, so care is required. Mechanical aids are available for harvesting in the form of gantries, picking ladders, and in some cases mobile conveyor systems, but more commonly the picker collects the fruit into a small holder such as a

Table 3.13. Crop losses in less-developed countries

Crop	Estimated Loss (%)
Apples	14
Avocados	43
Bananas	20–80
Cabbage	37
Carrots	44
Cassava	10–25
Cauliflower	49
Citrus	20–95
Grapes	27
Lettuce	62
Papayas	40–100
Plantain	35–100
Potatoes	5–40
Onions	16–35
Raisins	20–95
Stone fruit	28
Sweet potatoes	35–95
Tomatoes	5–50
Yams	10–60

Sources: [2, 4].

Table 3.14. Percentage losses of crops by reason between wholesale and retail markets in Thailand

	Weight	Bruise	Rot	Trim	Total
Cabbage	0.64	3.26	0.18	7.01	11.09
Cauliflower	0.98	0.62	0	9.76	11.36
Chinese cabbage	1.92	2.95	0.11	4.48	9.46
Spinach	2.77	1.06	0	14.43	18.26
Leaf mustard	3.92	4.69	0.29	4.11	13.01
Rape	2.13	2.62	0	3.32	8.07
Chives	1.28	3.18	0.15	5.63	10.24
Lettuce	1.32	2.48	0	2.50	6.30
Kale	1.22	2.55	0.14	8.21	12.12
Water spinach	1.40	3.96	0.27	3.23	8.86
Parsley	1.78	3.02	0.50	2.32	7.62
Spring onion	1.45	3.11	0.43	4.33	9.32
Cucumber	2.43	4.71	0.07	0	7.21
Gourd	0.50	7.59	0	0	8.07
Chinese radish	1.91	1.38	0.22	6.44	9.95
Chili	2.56	4.56	0.20	0.14	8.46
Tomato	0.41	9.03	0.05	0	9.49
Yard long bean	1.61	2.42	0	0	4.03
Mean	1.67	3.59	0.18	5.42	10.86

Sources: [3, 4].

Table 3.15. Example of postharvest operations for fresh fruit and vegetables

Postharvest Operations and Procedures	Example: Operational Steps for Apples
Harvest	1. Harvest
Field packaging	2. Transfer to field bin (or field sorting)
Transport out of field	3. Transport to packing shed
Packing shed operations	4. Reception 5. Drenching 6. Precooling 7. Unloading from field bin 8. Washing and drying 9. Waxing 10. Presorting (color, size range) 11. Sorting 12. Singulating 13. Grading to size 14. Packing 15. Labeling 16. Final shed quality control 17. Palletization
Storage	18. Cooling 19. Cool storage
Shipment to market	20. Loading and transportation
Retailing	21. Retailing operations

picking apron or bucket, which holds not more than 15 kg of fruit. Mangoes, papaya, apples, and fruit grown in tall trees can be harvested using picking poles: Fruit is separated from the tree by a sharp cutting edge on the end of the pole and falls into a net just under the cutter [4, 5]. In some countries fruit is harvested by hand, placed onto straw on the ground under the trees, hand-sorted, and packed into containers before leaving the orchard. Under these conditions consistent quality control is difficult to achieve among orchards, but fruit may sustain less handling damage. Fruit cleanliness also may be a problem.

Mechanical harvesters have been developed for many crops including apples, strawberries, blackcurrants, blueberries, cherries, and raspberries. Harvesting involves shaking the tree or cane by mechanical vibration and catching the detached fruit underneath in a large blanket or net [4]. However, these systems can cause significant damage to the crop and are generally only suitable for fruit to be used for processing. There are also difficulties if the fruit on the tree do not all ripen at the same time.

Some fresh vegetables are harvested by mechanical means. These include peas, beans, tomatoes, brussel sprouts, and root crops, particularly if the product is for processing. Details of such operations are provided elsewhere (e.g., by Thompson [4]). However, the risk of damage is great, and many fresh vegetables are harvested by hand cutting. In some cases (e.g., pumpkin, squash, cabbage, lettuce), after hand or machine cutting, the vegetables are placed onto a conveyor system that removes them from the field or to a mobile grading or packaging machine (Fig. 3.11).

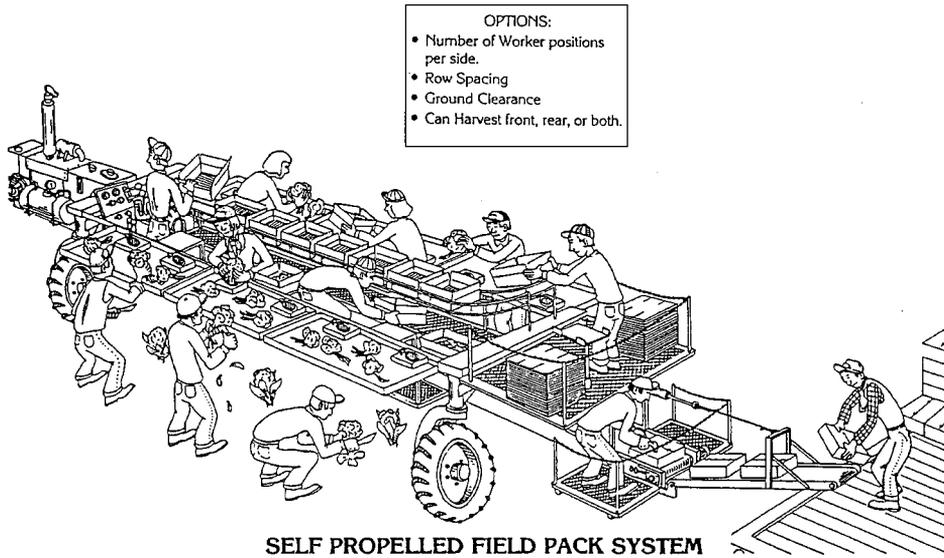


Figure 3.11. Self-propelled field pack system. (Source: Highlander Ramsay Welding Machine Promotional Brochure, 1993.)



Figure 3.12. Field Bin. One bin is partially submerged in a water dump using a fork lift truck. Fully automated systems also are used.

Transfer to Field Bin

Crops such as apples are collected into larger containers (field bins, Fig. 3.12), which are transported out of the orchard. The transfer into the field bin is a serious potential cause of damage, unless pickers are well trained. Fruit-on-fruit impact and impacts against the sides and base of the bin are potential sources of severe bruising.

Transport to Packing Shed

This journey also is potentially damaging to fruit. In most cases, the fruit as yet have no packaging to protect them, and they must be transported over rough farm tracks and other roads to the grading shed or market, which may be several kilometers away. Training and good management of drivers is essential to keep transport speeds to levels that are safe for the product.

Reception

It is vital to have documentation about a crop arriving at a grading shed. The documentation should record details of who the product is from, the harvest date, and the delivery date to the shed, as well as full details about the crop and pesticides used during its growth. This allows the grower to receive appropriate credit for the product and ensures that quality guidelines have been adhered to prior to arrival of the product at the shed. Spray certificates and other documentation also may be required. Reliable documentation requires careful inventory control, including clear procedures for recording all shipments and marking the field bins.

Precooling

If the product cannot be dealt with immediately when it arrives at the packing shed, it is essential to minimize the deterioration of product. For most crops this involves reducing the temperature. Sensible procedures include

- Harvesting early in the day (fruit will be coolest before sunrise, but fruit may damage more easily)
- Keeping fruit in shade (pole-frame structures with shade cloth coverings are a low-cost option)
- Dumping into cold water
- Placing fruit straight into precooler if fruit cannot be processed immediately

Highly perishable leafy vegetable crops can be cooled rapidly in the field using mobile vacuum coolers (see Section 3.4).

Drenching

Some varieties require fungicide or other preventative drenching to reduce physiological disorders or infestations. Calcium drenches are common for many crops. This can be done using an overhead spray system that washes through the field bin, or dipping the bin in a bath, which may be outside the grading shed.

Unloading from Field Bin or Trailer

This operation needs to be achieved with the minimum of damage. For apples, submerging the field bin in water results in little damage. Apples can be floated out and into channels using water (see Fig. 3.12). This procedure works well for fruit with a density less than that of water. Pears also can be removed in the same way, providing a suitable chemical is added to the water to increase its density. If water cannot be used, then options include tipping the bin over slowly or using side openings on the bin. Some systems have been developed using a false bottom, which is raised up inside the bin, so that fruit are removed from the top. Alternatively, bin inverters are used (e.g., Fig. 3.13).

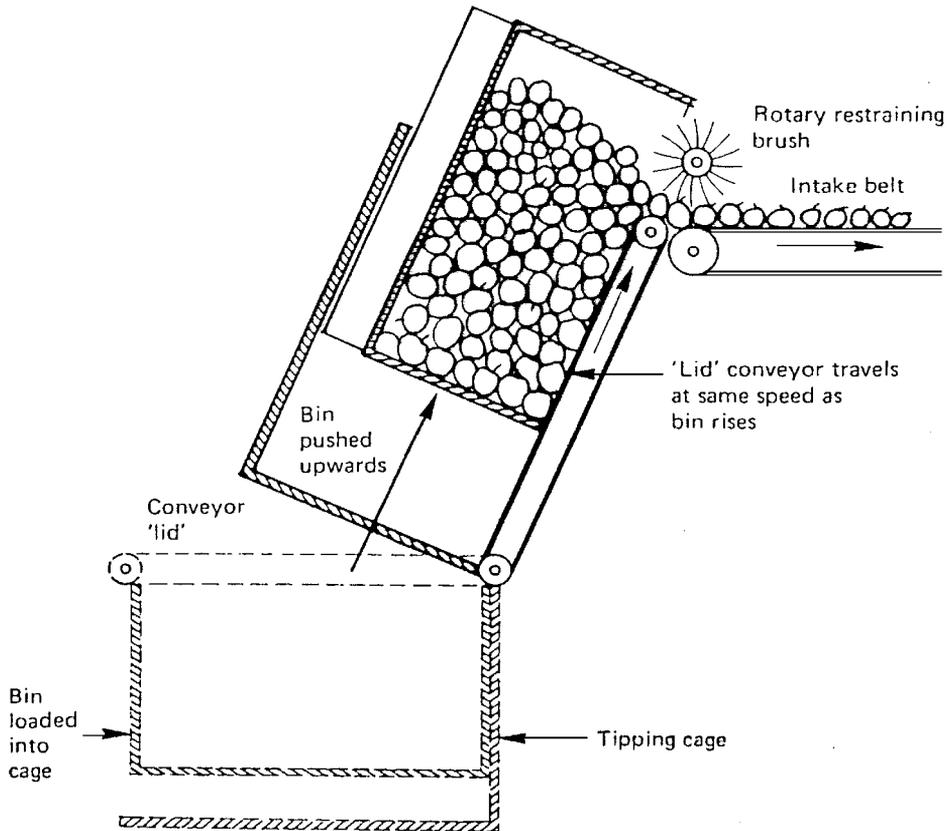


Figure 3.13. Bin inverter with restraining brush and conveyor "lid" to control flow of product.
(Source: Unknown)

Brushes can be used to control the rate at which fruit flows from the bin. However, these alternative methods are likely to result in damage to delicate crops.

Washing

Field dirt must be removed before sorting. Providing fruit is not seriously soiled, the water dump followed by a series of rotating brushes will remove dirt, without causing damage to the fruit. However, there is some concern that brushing can increase water loss from some products such as citrus. Also, the surface of some fruits (especially pears) is easily damaged by brushing or rubbing. Squash can be washed with a high-pressure water jet without apparent damage. After washing, surplus water should be removed. This usually is achieved as the fruit passes over the brushes or absorbant foam rollers but may require forced warm air from fans.

Waxing

Waxing of fruit is practiced mainly for cosmetic reasons, because it improves the appearance of the fruit to the customer (Fig. 3.14). Coatings also may reduce water loss and affect long-term color changes. Waxing is achieved by passing the fruit under

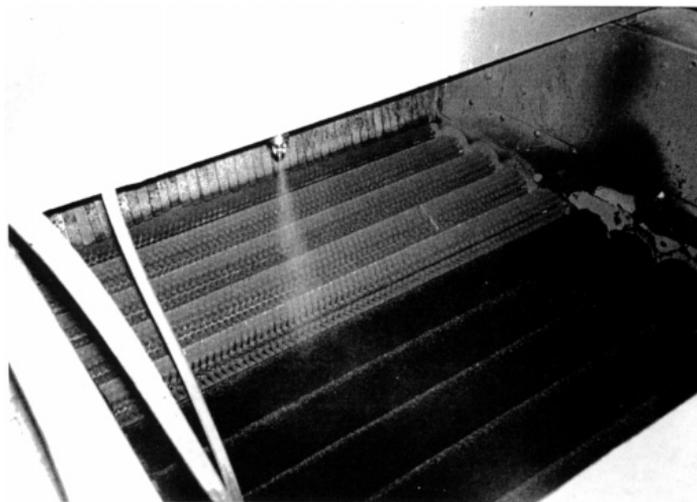


Figure 3.14. Waxing rollers. Two types are shown here.

wax-solution sprayers, combined with rotation on expanded plastic foam rollers already soaked by the spray.

Presorting

In large operations, presorting often is used to remove fruit that clearly does not meet quality standards. This process helps to maximize throughput in the rest of the grading system. Minimally trained graders can be utilized for this operation. Machine vision color sorters remove poor color fruit, and presizers remove excessively small or large fruit, before humans grade fruit according to quality standards. For some product lines, only presorting is necessary.

Sorting (grading)

During sorting, fruit are graded (sorted) into categories. In many cases there are only two or three grades (e.g., export, local market, or juicing). For some lines so-called fancy or premium grades are used. Although computer vision systems are making significant advances, grading still is best achieved in most cases by human inspection.

Sorters require suitable facilities to enable them to see defects clearly. Fruit must be rotated so that the sorters can see the entire fruit surface. Sorters will perform best if they work under good lighting conditions and in comfortable working positions [6]. Typical arrangements are shown in Fig. 3.15.

The reach required by the sorters should not exceed the distance between the tips of the fingers and the rear of the elbow, so that the sorter does not have to stretch or lean forward to reach fruit. It is normal practice to design such equipment using tables of anthropometric data for the type of people involved [7] (Table 3.16). Stretching further takes the sorter outside a region known as the *sustainable working zone*. The height of the working surface should be about 100 to 150 mm below the bottom of the elbow in the normal working position (sitting or standing). Reject chutes for substandard fruit should



(a)



(b)

Figure 3.15. Grading table design. (a) Example of poor layout. Lighting is uneven, and workers must raise poor fruit to place it in the reject line. (b) Side-to-side grader. Fruit moves from left to right of picture. Note barrier along center to limit worker's forward reach. Reject chute is at worker's waist. Note lighting is across table to give good uniform distribution.



(c)



(d)

Figure 3.15. (Cont.) (c) Cascade sorter. Fruit moves from left to right of picture towards worker. Forward reach is small. Lighting from behind may introduce shadow onto fruit. (d) Working height. All workers should be at the correct height using standing boards. Good seating should be provided, and workers should alternate between sitting and standing positions frequently.

Table 3.16. Selected static anthropometric dimension estimates for British adults aged 19 to 65 years (in millimeters)

	Men				Women			
	5th Percentile	50th Percentile	95th Percentile	SD	5th Percentile	50th Percentile	95th Percentile	SD
Stature	1625	1740	1855	70	1505	1610	1710	62
Eye height	1515	1630	1745	69	1405	1505	1610	61
Shoulder height	1315	1425	1535	66	1215	1310	1405	58
Elbow height	1005	1090	1180	52	930	1005	1085	46
Fingertip height	590	655	720	38	560	625	685	38
Sitting height	850	910	965	36	795	850	910	35
Sitting eye height	735	790	845	35	685	740	795	33
Sitting elbow height	195	245	295	31	185	235	280	29
Knee height	490	545	595	32	455	500	540	27
Shoulder–elbow length	330	365	395	20	300	330	360	17
Elbow–fingertip length	440	475	510	21	400	430	460	19
Upper limb length	720	780	840	36	655	705	760	32
Shoulder–grip length	610	665	715	32	555	600	650	29
Span	1655	1790	1925	83	1490	1605	1725	71
Elbow span	865	945	1020	47	780	850	920	43
Vertical grip reach (standing)	1925	2060	2190	80	1790	1905	2020	71
Vertical grip reach (sitting)	1145	1245	1340	60	1060	1150	1235	53
Forward grip reach	720	780	835	34	650	705	755	31

Source: [7].

be placed in a convenient position within the sustainable working zone, at the level of the table.

The color of the rollers on the table can affect the ability of the sorters to detect defects. In general, a neutral gray color is advisable, although both black and white rollers are used commercially. Highly reflective or white surfaces are not advisable as this causes eye strain; the eye compensates by reducing the iris so that less light is received from the fruit. Similarly, glare from fluorescent tubes should be avoided by locating the luminaries above the workers. The illumination should be uniform across the table. This is best achieved if fluorescent tubes are mounted at right angles to the path of the conveyor in a side-to-side table, and at a height of about 1.5 m above the table (see Fig. 3.15b).

Nicholas [8] recommended minimum light levels of 1000 lux at the table level. However, this level can cause eye strain if the rollers are white and highly reflective. If a dark background is used, the lux level can be doubled without causing strain; in this case

more light is received by the eye from the fruit, so that defect detection should be easier [9]. If graders are sorting for color, the fluorescent tubes used should not cause changes to the appearance. In comparison with sunlight, normal “cool white” tubes have a blue bias, which makes products appear too green to the grader [10].

The “Cascade” sorter design also is used for fruit (see Fig. 3.15c). This has the advantage that fruit is presented directly in front of the sorter. Only one person is able to inspect a particular fruit (whereas in the side-to-side design two or three sorters can inspect each fruit). This increases the responsibility of the sorter but also enables management to identify sorters who are consistently making errors, so that feedback and specific corrective training can be given.

Singulating

If fruit are to be sorted according to weight, the singulator separates fruit into pockets or cups so that each fruit can be weighed independently. The fruit can then be separated into appropriate sizes by sorting according to the weight recorded for the cup. Various devices including transfer wheels and expanding belts can be used for singulation.

Sorting into Size Bands

Customer preference internationally is for products that are sorted into sizes, either by weight or by dimension, according to the shape and regularity of the product. Conformity of size is particularly desirable for packaging and display purposes. Some fruits and vegetable cultivars have a consistent shape, so that they can be conveniently weighed and sorted. The result is a product that is consistent in volume and shape and packs easily. Electronic or mechanical methods can be used for weighing; shape sorters can be classified as mechanical or visual.

Electronic Weighing

In the electronic system all fruit are weighed at one point. Data is fed to a computer, which selects and preprograms the drop point. Fruit may rest on several fingers (rather than a single cup, as in Fig. 3.16), which are programmed to release the fruit at the required point, and the fruit rolls off sideways.

Mechanical Weighing

In a mechanical system, each fruit is “weighed” as it passes each exit point. A mechanical lever releases the fruit if the weight exceeds the preset trigger level at that point. Drop points therefore must be arranged along the line in increasing weight, which can cause logistical problems. Resetting the machine for different weight ranges also can be a slow process.

Mechanical systems are usually less costly and can be maintained and repaired by a trained mechanic. However, dust and wear can affect the weighing accuracy, so that weight bands are generally large. The operator must therefore allow a greater margin for error to avoid underweight cartons.

Comparison of Electronic and Mechanical Weighing

Compared with mechanical systems, the advantages of electronic systems are that

- The drop position can be selected to suit the shed design.

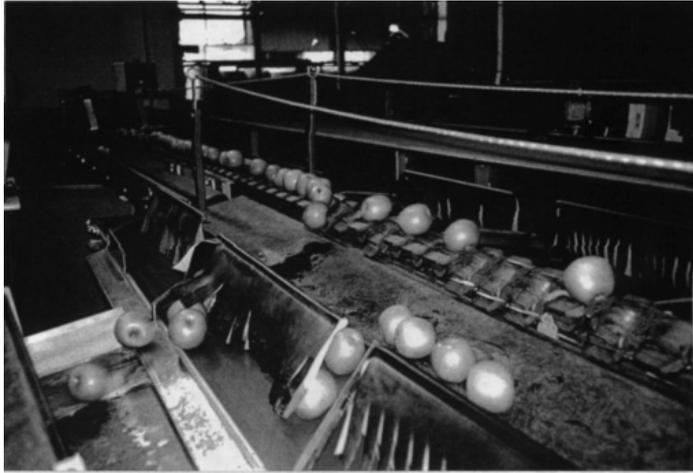


Figure 3.16. Single-line side-drop system for apples. This photo also shows overhead rubber fingers to reduce fruit velocity.

- It is simple to reprogram the system for a different size distribution of fruit (e.g., allow two or more drop positions for one fruit size if there is more fruit in that size).
- More accurate weighing can be achieved (most involve several repeats and averaging), reducing weight allowances.
- Faster flow rates are possible.
- Accurate count size records can be made automatically.
- It is possible to reduce the overfill allowance to a minimum.
- There is immediate feedback of performance data.
- The computer system enables other data to be stored at the same time to monitor performance of the whole shed operation.
- Quality-control problems can be detected rapidly, and rectification of problems is faster (hence fewer cartons may need to be repacked).
- Maintenance is more straightforward (by replacement of failed components).

Disadvantages are the cost, and the need for specialist computer and electronic service personnel.

In both systems fruit are dropped at an exit point by a mechanism that releases the cup so that the fruit falls downwards or sideways onto an exit conveyor belt (Fig. 3.16). On some machines, fruit fall into paper pulp trays or cartons directly. On others they fall into a rotating bin, from which they are packed into cartons by hand.

Sorting by Size

Some crops (e.g., tomatoes, carrots) produce inconsistent results if sorted by weight. Better results are obtained if they are sorted according to shape, using expanding screens or tapers. Fruit moves through the sorter and passes over or rolls along a continuously enlarging exit orifice until it is able to fall through into the appropriate container, such as in Fig. 3.17. In the field, crops also can be sized by eye, or by using a set of rings or plastic cards of predetermined size.

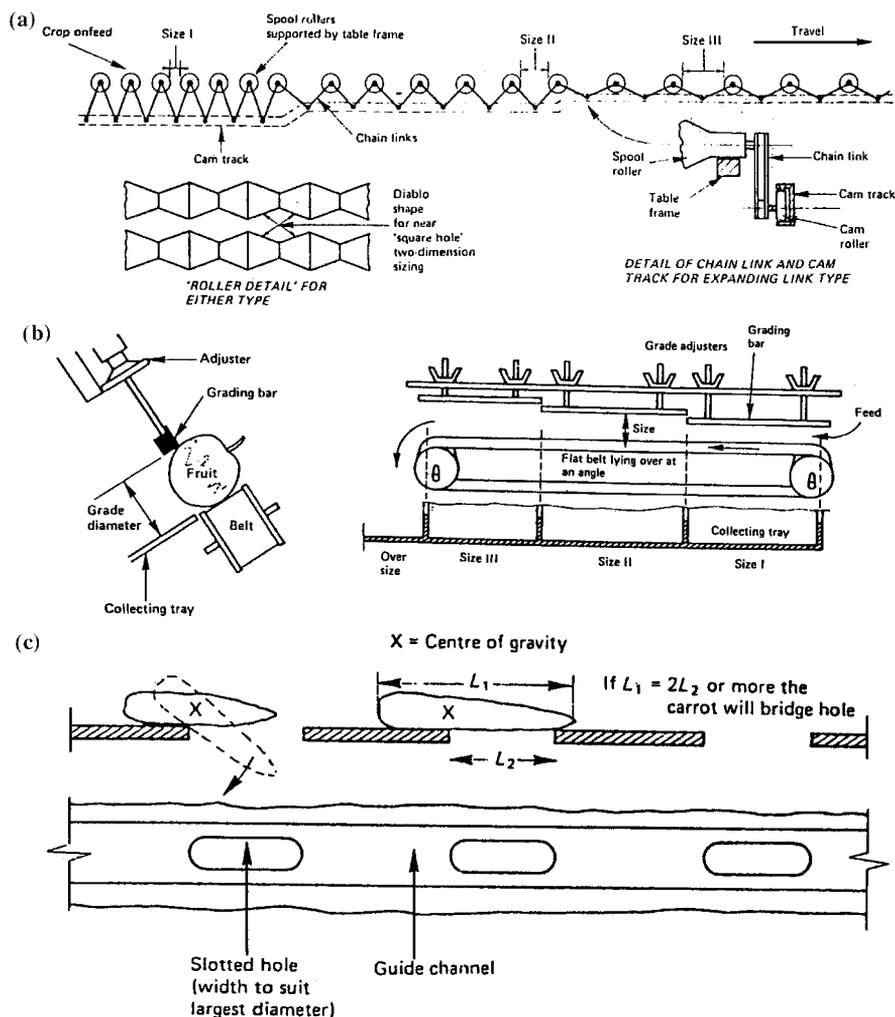


Figure 3.17. Size sorting. (a) Variable-aperture mechanical grader. (b) Spinning-fruit mechanical size grader. (c) Length grader.

Sorting by Image Analysis

Increasingly, image analysis is used to size fruit and vegetables. Cameras take a view of the product, and according to the algorithm the fruit is sorted according to cross-sectional area or according to some other shape factor (e.g., length). Other defects can also be detected (see Section 3.1.4).

Packaging

Once sorted into grades and size, fruit are delivered by conveyor to a packing area. Here fruit may be held in rotating final size bins until they can be packed by hand into

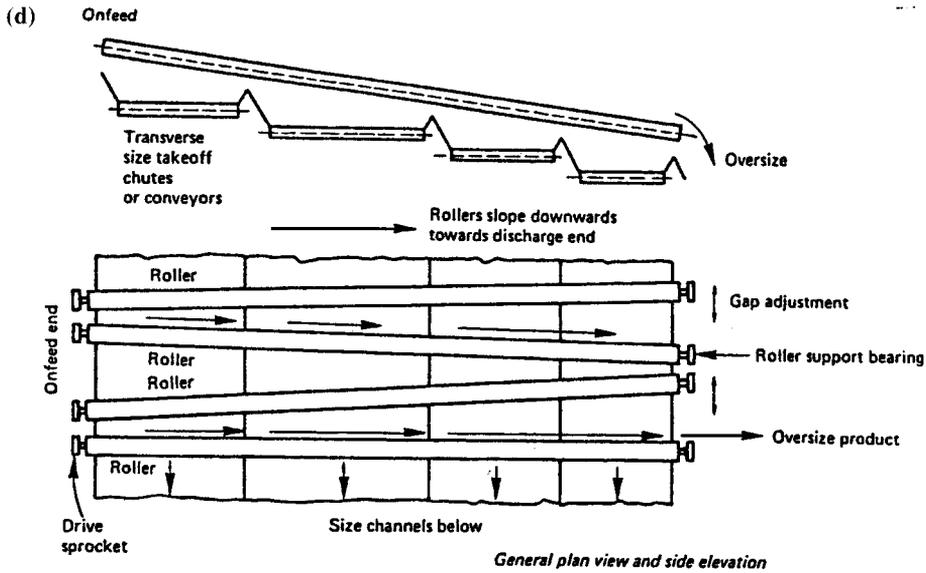


Figure 3.17. (Cont.) (d) Diverging roller grader. (Source: unknown)

cartons. Alternatively, if automatic tray fillers are used, fruit fall into a paper pulp tray directly, and a human packer checks the alignment of the fruit (e.g., the stem position may be upwards or to one side depending on the cultivar), and does a final brief quality check for missed defects before placing the loaded tray into a carton. Fruit and vegetables also may be wrapped individually in foam liners or films before, or instead of, packing them in a rigid container.

Packaging is a vital product component. It has a major influence on storage life and on the marketability of the product. Packaging fulfils several functions including containment, facilitating transportation, protection of fruit from further damage, protection of the environment from contents of package (for example, if the contents are dirty), marketing, product advertising, and stock control. These are discussed in Section 3.3.4.

Labeling

A key part of the postharvest process is to ensure that the product is clearly identified. On the international market, some fresh fruits require considerable detail. This may include, for example, harvest date, packing date, and name of grower and packer, as well as details about the cultivar and grade. This information can be critical if quality-management problems arise in the retail market.

Quality Control

Quality-control checks must be carried out before the fruit leaves the packing shed. In some industries, marketing organizations approve sheds with certificated inspectors, which reduces the need for additional checks made later in the chain (by which time corrective action is costly and difficult).

Although a check should be made once the fruit has been packed, good quality management requires that the process be continuous and cover all parts of the chain. Thus problems can be identified early and corrective action taken. Therefore an important part of a packing shed is an area set aside for quality-control inspection. This area needs to be as well lit and designed as the sorting-table area and should be in the center of activities so that the inspectors have close contact with the workers. However, it should also be designed so that the inspectors can work without disturbance from other activities.

Palletization

Cartons of fruit are increasingly palletized before distribution. This is discussed in Section 3.3.4.

Cooling

After packing fruit should be returned to the cool store. Even previously cooled fruit will have warmed up during sorting and will need recooling. For rapid cooling it is necessary to place fruit into a pre-cooler for fast cooling to store temperature, before transferring to the normal coolstore. Pre-coolers are designed to extract heat as quickly as possible and desirable by using directed forced air flow through the load to be cooled. Cool-storage systems are discussed subsequently. Cool stores may be located at the packing shed or at the distribution point for the region.

Coolstorage

Once at store temperature, fruit and vegetables can be transferred to a larger cool store. Its function is to maintain rather than reduce the temperature of the product. This is discussed in Section 3.4.

Loading and Transportation

Finally, product is loaded onto appropriate transportation by forklift truck and transported to the eventual market destination. This may be days or months after packing. Although the product usually has been packaged, it is still vulnerable to damage if subjected to rough rides over a considerable distance. Over long distances refrigerated vehicles are essential.

Wholesaling and Retailing

For many crops the worst handling takes place in the last part of the chain to the final consumer. Products are distributed to retailers through wholesale outlets that may not be suited to long-term storage or handling. Products usually are inspected superficially, and bulk loads are broken down for shipment to retail outlets. Thus a great deal of handling is likely to occur under unfavorable conditions. Modern systems require that packaging be designed with these factors in mind.

The final handling step is to put products on display for the consumer. At this stage the packaging may be removed or damaged as it is opened. For example, if apples are tipped out of cartons into retail displays and then allowed to be handled by customers, the amount of bruising damage becomes extremely high. To overcome this problem, some products are being marketed in "retail trade display" cartons, which are designed to fit the space available on the retail shelving. They hold fruit only one or two layers deep, so that it is not necessary to remove fruit from the packaging.

Vegetables are generally less sensitive to handling damage, and so rougher handling seems to be acceptable at this point in the chain. However, moisture loss and product deterioration may result, particularly if vegetables are not displayed under appropriate temperature and high-humidity conditions. Much retail shelving includes overhead misting to maintain product freshness. For optimum product quality the volume of product on display should be determined to match the demand, so that products only spend a short time on display before they are purchased. Customers should have a limited selection to reduce the amount of “picking over.” Shelves then need to be replenished at regular intervals, with fresh product placed beside or under rather than on top of the older product on display. The remainder of the stock should be stored in appropriate cool stores at the rear of the shop.

3.3.3 Handling Damage

Most fresh fruit and vegetables are damaged by rough handling. Although standards are less rigorous for products destined for processing, serious damage is not acceptable, because this can result in off-flavors or discoloration in canned products. Vegetables often are susceptible to handling damage, producing effects that are not obvious. Fruit and vegetables must be handled several times. At each point there is a risk of damage. Various types of mechanical stressing can occur as listed in Table 3.17. The main concerns are compression loading under impact and static loading. Rubbing and tensile stresses are additional problems in a few products.

Types of Handling Damage

Bruising is a well-known type of damage found in fruits and vegetables. A bruise is an area of damage usually caused by compression or impact. The result of mechanical

Table 3.17. Types of loading and effects on products

Mode of Loading	Impact (Irregular one-time events) Pulse duration (typically 0.5–10 ms)	Continuous Vibration (Similar sinusoidal events repeated regularly over an extended period of time) Frequencies from 0.1–10 ⁶ Hz	Static or Quasistatic Loading Constant Loading
Compression	Predominant in all handling systems; major cause of damage	Transportation; Probable cause of damage in some crops	All times, especially in storage; affects some products especially in jumble pack
Tension	Blows on sharp edges; part of fruit tissue may be under tension—carrots and long products in bending	Possibly during unloading part of vibration cycle unknown effects	Rare except in bending in elongated products (e.g., carrots); in storage, internal stresses can cause cracks and splits
Shear	Glancing blows; sharp objects causing cutting; rubbing	Rubbing against brushes, branches, packaging, and other fruit; causes surface-damage problem in some crops (e.g., pears, citrus)	In storage; nonnormal loading; especially in jumble pack will deform soft products

Table 3.18. Effects of latent damage due to poor handling and postharvest systems

Type of Damage	Effects
Bruising	Surface discoloration, softening, deformation; internal breakdown, discoloration, moisture loss; increased ethylene production
Cuts and punctures	Scarring; site of infection for molds; water loss
Abrasion	Skin browning (pears)
Preharvest stress and nutrition problems	Browning; internal breakdown
Chilling injury (too-low storage temperature)	Pitting; internal breakdown; incomplete ripening; off flavor; decay (tropical crops)
Heat injury (overheating)	Ripening failure (tomatoes)
Anaerobic conditions	Internal browning; blackspot

damage is generally to rupture or damage cells. In many fruits (including apples), polyphenoloxidases oxidize phenolic compounds to unstable quinones, which polymerize as melanic compounds with a high molecular weight, causing browning [11, 12]. The browning takes a few hours to develop and is then clearly visible in tissue when the fruit is sectioned, or when the skin is removed. In many fruit crops the damage may be difficult to see, particularly at the time the damage is done. However, it results in a reduction in storage life, and loss of eating quality. For example, handling damage to bananas leads to blackening of the skin and uneven ripening. Uneven ripening also occurs as a result of rough handling of green tomatoes. During harvesting, kiwifruit appear to be hard and unlikely to be damaged. However, impact at harvest results in the increased incidence of soft patches on the fruit in later storage [13]. In peaches, potatoes, tomatoes, and papaya, bruising damage often is internal (in uniformly textured products this occurs at a depth of about half the contact radius, at the site of maximum shear stress in compression) and is not visible from the surface. Bruising of citrus, cherries, and tomatoes can cause an increase in CO₂ emission. Hung [14] has discussed these and other types of latent damage in fresh products (Table 3.18).

One issue to be considered is the difference between scientifically measurable damage and damage that is commercially significant. For example, in European onions, impact damage increases moisture loss, but this is unlikely to concern the consumer. However, it reduces the total saleable weight and hence affects the return to the grower. At least in the short term, impact damage does not affect the market price of the product, because the damage is not apparent. However, in potatoes, internal black spots are produced, and this may affect future purchasing. Apple bruise size can be determined readily by sectioning to measure the volume [15]. Most scientists assess bruising in this way. However, industrial requirements generally are based on the area of the bruise visible before the skin is removed. In many apple cultivars this is often difficult to determine, particularly if the threshold bruise area is small. Appropriate bruising assessment methods must take this into account. This is discussed subsequently.

Measurements of Physical Damage

Where a damaged spot is clearly defined, the volume can be estimated by sectioning and measurement. At least three alternative expressions have been used.

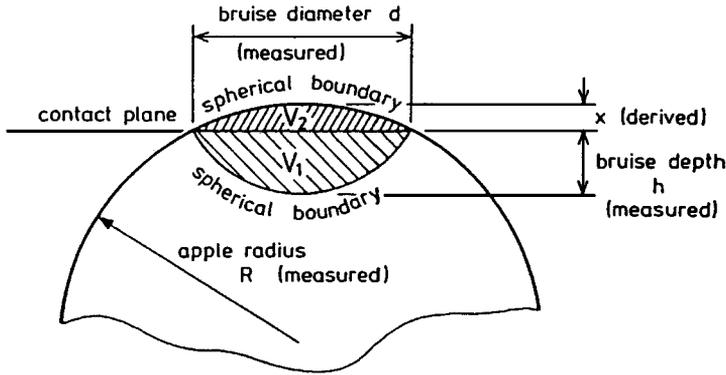


Figure 3.18. Model of a bruise or damaged region of fruit (Source: [18, 19]).

Bruise volume has been measured by excavating the bruised tissue and measuring the mass [16]. However, this method is too time-consuming for practical purposes and is subject to human error. Normally bruise volume is measured by making a radial cut through the center of the bruise area, followed by width and depth measurement. Bruise volume then is calculated by assuming a geometric shape. A number of methods for calculating bruise volume have been suggested.

Mohsenin [17] defined the bruise volume V_b (m^3) based on the assumption that the shape of the bruise was part of a spheroid. This gives:

$$V_b = \frac{\pi h(3d^2 + 4h^2)}{24} \quad (3.7)$$

where h is the depth of bruise at the center (m), and d the surface diameter of the bruise (m) (Fig. 3.18).

Equation (3.7) ignores the curvature of the fruit. Holt and Schoorl [18, 19] corrected for this by assuming that the bruise is spherical above and below the contact plane (volumes V_1 and V_2 in Fig. 3.18). The total bruise volume in cubic meters then is given by:

$$V_b = \frac{\pi h(d^2 + 4h^2)}{24} + \frac{\pi X(3d^2 + 4X^2)}{24} \quad (3.8)$$

where h is the height of the bruise below the contact plane in meters and X is the height of the bruise above the contact plane in meters and can be calculated from

$$X = R - \frac{R^2 - d^2}{4} \quad (3.9)$$

where R is the radius of curvature of the fruit in the region of the bruise in m.

A simpler formula is found if the damaged volume is assumed to be a semi-oblate spheroid [20], for which the bruise volume is given by

$$V_b = \frac{\pi h d^2}{6} \quad (3.10)$$

Except for deep bruises, Eq. (3.10) is a poor representation of bruise shape.

Sometimes fruit damage appears as a region below an undamaged region of tissue. In this case, the damaged area can be calculated by subtracting the undamaged region.

Commercially significant damage affects the quality (and hence the price) of the fruit. Because quality involves meeting the requirements of a discerning customer [21, 22], ultimately it is the perception and assessment of the damage by the customer that is the dominant factor. Currently, with the exception of the person who eventually eats the fruit, most judgments of damage are based on visual perception, sometimes combined with feeling fruit to detect soft patches, but without internal incision. Thus, although in a laboratory it is easy to measure the damaged volume of tissue after removal of skin, industry requirements generally are based on the visible surface size of a bruised or damaged region before the skin is removed. Often bruises can be sensed by humans through observing irregularities in the surface reflection pattern of light from a bright light source, rather than from a color change. In many products the perceived area of damage is difficult to determine, particularly if the threshold bruise area is small.

For many products, measurement of the extent of damage can be difficult. If a volume or area measurement is not obvious, then the experimenter may need to resort to a suitable scale to indicate the severity of damage. If different types of damage occur, alternative criteria to describe damage quantitatively are required. For some crops (e.g., tomatoes), damage scales can be developed based on the type and visibility of damage, rather than the size of the damage area. The scale should involve damage descriptions and preferably photographs of typical fruit exhibiting the level of damage representing each level on the scale.

Damage-Measurement Parameters

Holt and Schoorl [18] demonstrated that bruise volume in apples is related to the energy absorbed by the apples in both impact and slow (quasistatic) loading. In an impact the absorbed energy can be determined if the impact and rebound energies are known, and if there are no other energy absorption mechanisms. In general

$$E_{\text{abs}} = E_0 - E_{\text{Reb}} - E' \quad (3.11)$$

where E_{abs} , E_0 , E_{Reb} , and E' refer to the absorbed, initial, and rebound energies, respectively (J), and E' includes any other energy-absorbing mechanisms, such as cushioning or vibration of supports and pendulum arms.

In slow loading conditions, the energy absorbed is the strain energy of the loading [18, 19]. This is given by

$$E_{\text{abs}} = \oint V_s \sigma d\varepsilon \quad (3.12)$$

where σ and ε are the stress (Pa) and strain (m/m) from the loading cycle, and V_s is the volume of the compression test sample (m^3).

In most products the bruise volume depends on the rate of loading. Greater damage is done by the same absorbed energy if products are loaded slowly. Even so, impact loading is more likely to be the cause of bruising in fruits and some vegetables, because

dynamic loading is more frequent during the lifetime of the fruit, and the impact forces are much higher if the product is firm. This is illustrated in a subsequent subsection.

The bruise susceptibility of a product, B (in m^3/J), can be defined by the equation:

$$V_b = BE_{\text{abs}} \quad (3.13)$$

Schoorl and Holt [19] called B the *bruise resistance*. However, this is not appropriate, because the bruise volume increases as the bruise resistance increases, and therefore the term *bruise susceptibility* is preferred.

Equation (3.13) works fairly well at high energy levels and is useful in studying damage to apples and other fruit and vegetables during transportation in cartons [23]. However, it does not consider the surface area of the bruise and does not indicate bruise initiation at low energy levels, or even what the threshold bruising levels may be. Also, in practice, absorbed energy is affected by the mechanical properties of the product (hence making it a model output rather than input), and the parameter is of little importance to the industry, because fruit are subjected to fixed drop heights during handling. Thus, impact energy is a more useful factor, although there are difficulties with this parameter (as discussed subsequently).

The requirement for surface area data can be overcome by introducing the term *bruise-area susceptibility* (B_{AS} , in $\text{m}^2/\text{J}^{2/3}$) [24]. A further modification is to replace E_{abs} in Eq. (2.13) with the impact energy (E), so that the bruise surface area (A) can be written as:

$$A = B_{\text{AS}} \cdot E^{2/3} \quad (3.14)$$

where the power term in E is based on the assumption that bruises are geometrically similar in three dimensions. Equation (3.14) is a more useful version of Eq. (3.13) but is less rigorous scientifically. Problems with Eq. (3.14) can arise because other factors affect the bruise surface area (as is discussed in the next subsection).

Siyami *et al.* [25] obtained a reasonable prediction of bruise surface area of apples by using an empirical linear-regression model of the acceleration and velocity change measured with force transducers, together with penetrometer force and diameter. Other models have included a probability model to describe the threshold of bruising [26] and a cell-failure model [27]. These, and Eqs. (3.7) through (3.13), can be used for firm fruit and vegetables.

Factors Affecting Damage

Indenter Shape

Bruise susceptibility in apples and pears is affected by indenter shape [28, 29]. Higher bruise volumes are recorded if the radius of curvature or contact angle of the side of the indenter is increased. This affects the bruise surface area susceptibility appreciably.

Product Size and Curvature

Various attempts have been made to develop models to predict the bruise surface area from other parameters. The theory of elasticity has been used to predict the area of contact between two elastic curved surfaces [30]. The bruise surface area is usually similar to the contact area, depending on the nature of the impact.

In dynamic situations, mass is a factor in the extent of bruising, because impact energy is proportional to mass. However, mass is not likely to affect bruise susceptibility, unless larger fruit differ in mechanical and chemical composition compared with smaller fruit. Mass effects can be confused with maturity effects, because more mature fruit and vegetables also may tend to be larger if they have been allowed more time to grow.

Bruise Color and Visibility

The chemical reaction causing bruising depends on the level of phenolic compounds in the tissue, and the availability of oxygen. There is some evidence to suggest that the extent of browning may depend on preharvest factors [31] as well as cultivar effects. Bruise visibility may be affected by the optical transmissivity of the skin and by skin pigmentation and it may decrease with time.

A model may be defined in terms of the commercial bruise susceptibility (B_{CS} in $m^2/J^{2/3}$) [32]:

$$B_{CS} = f(B_P) \cdot B_{AS} \quad (3.15)$$

where B_P is a bruise visibility factor, and

$$B_{AS} = f(\text{cell wall strength}) \cdot f(\text{turgor pressure}) \cdot f(\text{fruit geometry}) \quad (3.16)$$

Weight Loss in Storage

Moisture loss in storage reduces the bruise threshold of apples [33, 34]. This suggests that controlled water loss may help to reduce handling damage in fresh fruit.

Threshold of Bruising

Studies of apples often involve high-impact energies above 0.1 J, so that bruises are clearly visible. However, the threshold of visible damage, rather than the onset and extent of subsurface damage, is important to the industry. Probability models have been used to define the onset of bruising in apples [34]. Another approach is to drop fruit from a geometric progression of heights using a pendulum system. After each impact fruit are inspected and rated according to the appearance of bruises. Experiments have shown that this approach gives results that can be related to bruising levels found commercially [24].

For other fruits and vegetables similar results are likely. It is therefore important that product testing conditions are designed to measure factors that are important for the particular product. For example, a rotating drum system has been developed to represent grader loading [35].

There are many factors that can alter the amount of impact damage to products. These are listed in Table 3.19. Important information for fruit and vegetables should include guidance on effects of temperature, maturity at harvest, and storage time on damage levels. These are discussed further subsequently. Seasonal and cultivar effects also should be understood. The effects of preharvest and postharvest factors on bruising in apples are listed in Table 3.20. Bruise susceptibilities for various apple cultivars are given in Table 3.21.

It is helpful to use a scientific approach to the study of damage, by considering the mechanical theory of damage.

Table 3.19. Factors affecting damage in fruit and vegetables

Environmental Factors	Whole-Fruit Factors	Internal Factors
Temperature	Cultivar	Cell wall strength
Stress loading rate	Density	Cell wall elasticity
Indenter shape (sphere, flat, cylinder)	Mass	Cell shape, size and orientation
Energy (drop height)	Volume	Intracellular bonding
Storage conditions	Maturity	Turgor
Repeated loading	Product structure	Internal structure
Preharvest and postharvest treatments	Chemical composition	Air space volume and air distribution
Customer perceptions of damage	Damage visibility	Surface curvature Skin strength

Source: [36].

Table 3.20. Effects of factors damaging apples

Factors affecting apples	Effect
Preharvest	
Irrigation	Slightly increased bruise susceptibility
Mineral nutrition (calcium and phosphorus sprays)	No effects found
Time of day of harvest	Slightly less bruising in midmorning and early afternoon, compared with early morning
Postharvest	
Delay after harvest before cooling/handling	Large reduction (20%) in bruising after 24 hours
Fruit temperature during grading	More damage if graded cool
Relative humidity in storage	More damage in fruit stored at high humidity

Source: [36].

Mechanics of Fruit Movement

Newton's laws of motion can be used to describe the movement of fruit and vegetables, and to model impacts against other objects. Thus,

$$E = \frac{M \cdot U^2}{2} = Mg \cdot H \quad (3.17)$$

where E is the impact energy (J), M is the mass (kg), U is the impact velocity (m/s), g is $9.81 \text{ m} \cdot \text{s}^{-2}$, and H is the effective free-fall drop height. Energy is conserved in every impact but may be converted to other forms such as damage, sound, heat, or plastic deformation.

In a rotating object (e.g., a fruit rolling down a slope) energy is associated with the rotation of the fruit. This is given by

$$E_R = \frac{I \cdot Q^2}{2} \quad (3.18)$$

Table 3.21. Reported range of bruise susceptibilities of apples cultivars

Cultivar	Test Energy (J)	Bruise Susceptibility (mL/J)
Splendour		
Fresh	0.31	2.9
Stored, low humidity	0.31	2.2
Stored, high humidity	0.31	3.3
Splendour ^a	0.1–0.6	3.0
Braeburn		
Fresh	0.31	1.7
Stored, low humidity	0.31	1.6
Stored, high humidity	0.31	2.0
Granny Smith		
Fresh	0.31	2.5
Stored, high humidity	0.31	2.9
Granny Smith ^a	0.78	7.6–9.2 ^b
Golden Delicious ^a	0.009–0.49	0.9–9.8
Golden Delicious ^a	0.47	4.3–6.6
Golden Delicious (late) ^a	0.047–0.42	2.6
Bramley's Seedling ^a	0.19	3.0–4.1
McIntosh ^a	0.009–0.49	1.5–10.8

Sources: [34] except as marked.

^a Data from various studies reported by Lincoln Technology (New Zealand).

^b Based on absorbed energy; others based on total energy.

where E_R is rotational energy (J), Q is angular rotation in radians per second, and I is the moment of inertia ($\text{kg} \cdot \text{m}^2$), which for a spherical object of radius r (m) is given by

$$I = \frac{7 \cdot M \cdot r^2}{5} \text{ (rolling)} \quad (3.19)$$

$$I = \frac{2 \cdot M \cdot r^2}{5} \text{ (spinning about center)}. \quad (3.20)$$

The momentum T ($\text{N} \cdot \text{s}$) of an object with velocity U (m/s) is given by:

$$T = M \cdot U \quad (3.21)$$

In an impact momentum is always conserved (this is a very helpful fact for predicting dynamic movement after a collision).

Quasistatic Loading

Under slow loading conditions the behavior of most fruit and vegetables is nonelastic. Energy absorbed during a loading cycle can be determined from the area enclosed by the stress–strain curve and is given by Eq. (3.12). This represents the hysteresis in the loading and unloading cycle. In many fruits the absorbed energy is related to the level

of damage to the tissue, unless other mechanisms are acting that do not cause damage [21]. These could include permanent deformation without cell damage. Providing the relationship between stress (σ) and strain (ε) is known, this can be calculated. However, the relationship is complex. A number of models have been used to describe it, including the Maxwell and Kelvin models and their derivatives [17].

Analysis of Compression Loading

A starting point for estimation of fruit damage during handling is Hertz's general theory of the elastic contact of two curved surfaces [30]. The radius of the contact area between two spheres is given by:

$$a = \sqrt[3]{\frac{3 \cdot \pi \cdot F \cdot R \cdot k}{4}} \quad (3.22)$$

where

$$k = \frac{1 - \nu_1^2}{\pi \cdot Y_1} + \frac{1 - \nu_2^2}{\pi \cdot Y_2} \quad (3.23)$$

and

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \quad (3.24)$$

where R is the relative radius of curvature of the two surfaces (m), R_1 and R_2 are the radii of curvature of the two surfaces in the contact area (m), Y is the modulus of elasticity (Pa), ν is the Poisson's ratio of the material, F is the applied force (N), and the subscripts 1 and 2 refer to the two objects. Values of Y and ν for fruits are given in Table 3.A4 in the Appendix.

The analysis is valid only if the fruit behaves perfectly elastically. Fruits are generally viscoelastic in behavior, but in an impact (at least up to the point of tissue failure), the elastic model is useful for predicting the contact area. This enables a calculation of the size of the damaged area, because the two are closely related. In quasistatic loading, stress relaxation is likely to occur, and so the elastic model is not particularly helpful. Modified formula have been developed to allow for viscous effects [25]. If the surfaces are not spherical a small correction is needed [17], but within experimental error this usually can be ignored. An effective radius of curvature can be found if the radii of curvature (R_{1A} and R_{1B} in meters) in two orthogonal directions are measured, and the equivalent curvature determined from

$$\frac{1}{R_1} = \frac{1}{R_{1A}} + \frac{1}{R_{1B}} \quad (3.25)$$

with a similar formula for R_2 . For a more precise analysis see Table 3.A2 in the Appendix.

Impact Loading

Impact mechanics provides a simple explanation of fruit damage. Newton's second law can be written as

$$F = M \cdot \frac{du}{dt} \quad (3.26)$$

where M is the mass (kg), t is time (s), and u is the velocity (m/s) of an object striking a rigid object. Integrating gives

$$\int F \cdot dt = M(U' - U) \quad (3.27)$$

where U is the initial velocity and U' is the velocity after impact (m/s). The right-hand side of Eq. (3.27) is the momentum change, and the left-hand side is the area under the force–time curve for the impact, known as the *impulse*. If a fruit strikes an object, its velocity must be changed to arrest its movement, and so the momentum change is determined by the geometrical constraints and the path of movement of the fruit. The extent to which the fruit rebounds depends on the level of elasticity of the impact (i.e., the loss of energy). A useful parameter to determine this is the coefficient of restitution, e , defined by

$$e = \frac{\text{velocity of separation}}{\text{velocity of approach}} \quad (3.28)$$

where $0 \leq e \leq 1$. For a perfectly elastic impact $e = 1$, and the kinetic energy is conserved. The value of e depends on the two surfaces in contact, and the severity of the impact. In apples values range from 0.9 for very gentle impacts to 0.4 or less for impacts in which considerable damage is done. For two different materials e is given by [17]

$$e_{12} = \frac{e_{11}Y_2 + e_{22}Y_1}{Y_1 + Y_2} \quad (3.29)$$

where e_{11} refers to the first material striking itself, Y is the elastic modulus (Pa), and the subscripts refer to the first and second materials.

When two finite masses impact, the kinetic energy loss (J) is given by

$$\Delta E = \frac{(1 - e^2)M_1M_2(U_1 - U_2)^2}{2(M_1 + M_2)} \quad (3.30)$$

where the subscripts refer to the first and second masses (kg) [17].

Once e is fixed, the total momentum change is determined, and so is the total impulse. However, both F and t depend on the surfaces. The area under the curve depends on the nature of the surfaces and their curvature in the impact area, as well as the kinetic energy of the impact. In an impact the total time of the impact can be very small, so F must be correspondingly larger. Soft surfaces that cushion the impact are effective because they increase the duration of contact. Figure 3.19 shows examples of idealized impulses for various impacts of a sphere onto a flat surface.

In Fig. 3.19a both curves are symmetrical and the impact is perfectly elastic—that is, the sphere rebounds at the same speed with which it struck ($e = 1$). In Fig. 3.19b, in the curve with $0 < e < 1$, there is some nonelastic behavior. The peak may be flattened or irregular and extended. The pulse is no longer symmetrical, and the rebound speed is less than the impact speed. The peak force recorded may not coincide with the point

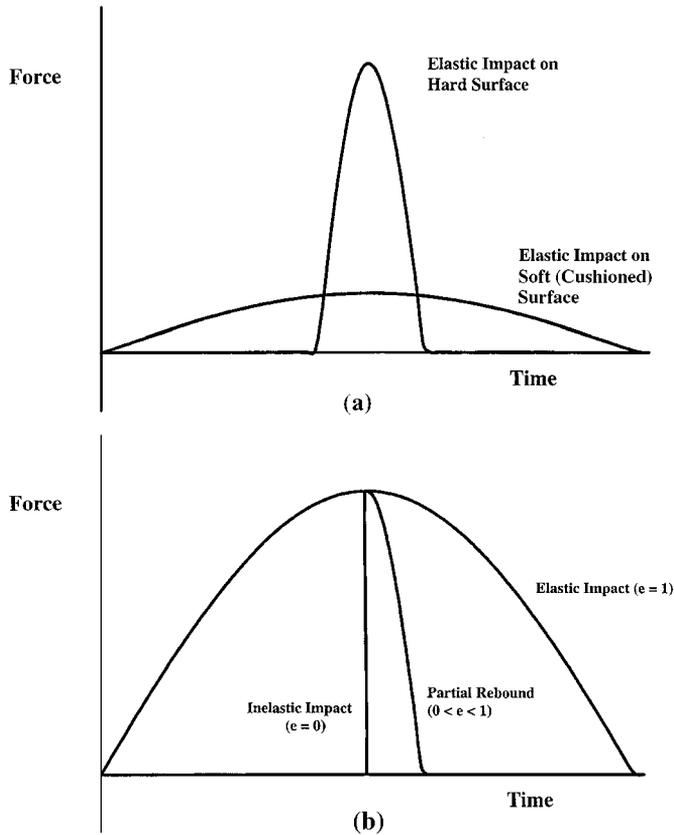


Figure 3.19. Schematic force–time curves for impacts. (a) Typical impact curves for fruit or vegetable striking hard and soft surfaces with a high coefficient of restitution. (b) Impacts with various coefficients of restitution.

of closest approach in this case, because the fruit structure may collapse so that the load falls with continuing penetration. If $e = 0$, there is no rebound.

In practice, if a firm fruit strikes a hard surface, F can be surprisingly large. For example, the force produced when a 100-g apple falls 200 mm onto a hard surface can be of the order of 200 to 500 N. The force can be reduced greatly by extending the duration of the impact (by cushioning) as in Fig. 3.19a.

However, tissue damage is caused by excessive stress, and so if the contacting surfaces conform closely, the fruit need not be damaged even though the force is high. From Eq. (3.21) elasticity theory predicts that the maximum force is given by

$$F = n \cdot x^{3/2} \quad (3.31)$$

The duration of the impact is given by

$$t = \frac{2.94x}{U} \quad (3.32)$$

where x is the distance of closest approach (m) given by

$$x = \left(\frac{5 M U^2}{4 n} \right)^{2/5} \quad (3.33)$$

and where

$$\frac{1}{M} = \frac{1}{M_1} + \frac{1}{M_2} \quad (3.34)$$

and

$$n = \frac{4R^{1/2}}{3\pi k} \quad (3.35)$$

where k is a constant given by Eq. (3.23), M is mass dropped (kg), H is drop height (m), Y is Young's modulus (Pa), and R is the effective radius of curvature (m). Thus, from Eqs. (3.31) through (3.35)

$$F = \left(\frac{125 R M^3 U^6}{36 \pi^2 k^2} \right)^{1/5} \quad (3.36)$$

$$a = 1.24(R^2 M U^2 k)^{1/5} \quad (3.37)$$

where a is the contact radius (m). The maximum pressure on the contact area is at the center of contact and is given by

$$P_{\max} = 1.5P = 0.2515 \left(\frac{U^2 M}{k^4 R^3} \right)^{1/5} \quad (3.38)$$

Despite its assumptions, the model predicts the contact area surprisingly well, to within 15%. As an example, the following results arise from the formulae for an apple (mass 200 g, radius 80 mm, with $Y = 9.1$ MPa, $\nu = 0.3$) striking a steel plate ($Y = 200$ GPa, $\nu = 0.3$) from a drop height of 300 mm

$$\begin{array}{ll} U = 2.425 \text{ m/s} & \text{Area} = 394 \text{ mm}^2 \\ F = 469 \text{ N} & P_{\max} = 1.79 \text{ MPa} \\ a = 11.2 \text{ mm} & t = 3.80 \text{ ms} \end{array}$$

According to elasticity theory, failure occurs at a pressure of $1.06 \sigma_Y$, where σ_Y is the yield stress measured in a compression test on a cylindrical sample of tissue [37]. Failure occurs below the surface at a depth of half the contact diameter and arises at this point because of the hydrostatic nature of the stress field immediately below the indenter, and the resulting complexity of the shear stress distribution.

Other attempts have been made to correct for viscous effects, but with little improvement to the accuracy of the model. For example, Siyami *et al.* [25] suggested modifications to the basic model to allow for viscoelastic effects, obtaining

$$a = K_1 \cdot (H \cdot M \cdot R)^{1/4} \cdot F_m^{1/4} \quad (3.39)$$

where F_m is the Magness Taylor penetrometer force (N) and K_1 is a constant. Equation

(3.39) gives only a slightly better correlation than the elasticity model (Eq. [3.37]) for apples.

These models demonstrate that the diameter or relative radius of curvature of the fruit and the impacting surface have a significant effect on the bruise surface area, even if there is no effect on the bruise susceptibility (which appears to be the case in apples [38]). This has implications for the commercial assessment of bruising.

Impact Energy

Many researchers report impact energy rather than absorbed energy. This is partly driven by pragmatism, because the design of handling-equipment systems requires the specification of acceptable drop heights for fruit. These are determined from maximum velocity and thus kinetic energy considerations. In addition, some experimental designs render absorbed energy unmeasurable (e.g., where a sphere is dropped down a plastic tube [35]). Unfortunately, impact energy is ambiguous in two-body impacts, because it depends on the frame of reference of the observer, as a simple example shows: If two apples of the same mass M kg impact at a relative speed of u m/s, the impact energy is $0.5 M \cdot u^2$, but if both apples are viewed as moving towards each other with velocity $u/2$, the impact energy in this reference frame is only $0.25 M \cdot u^2$. In cases in which one object is regarded as being infinitely massive, the ambiguity is removed, but in cases in which the colliding surfaces are of similar mass (especially in the case of apple-to-apple impact), the practice of determining the kinetic energy as if only one object is moving leads to inconsistencies. A more suitable reference frame in these cases is the zero-momentum reference frame defined by $\Sigma(M \cdot u) = 0$. Use of this frame results in the impact energy being a minimum. If absorbed energy is used, the inconsistency is removed, because its value is independent of the reference frame.

3.3.4 Packaging

Packaging is needed for fresh fruit products throughout the postharvest chain. The producer must use some means to get bulk product to market, while the consumer must be able to carry fruit home without serious damage. Packages can be in a range of sizes. For a single person, a package weighing up to 20 kg is easy to handle. Larger packages can be carried, with some effort, up to around 40 kg, and in some markets even packages of 100 kg or more are carried by hand. In less developed countries more fruit is handled unpackaged on local markets (e.g., pineapple, cucumber, banana hands), but export fruit usually requires packaging.

Although some fresh products (e.g., squash, pumpkins, oranges, potatoes) are transported to market in bulk, this practice inevitably causes some damage. A range of packaging systems are used for fresh fruit and vegetables.

Because fresh produce is alive, it is essential that the microenvironment around the product is suitable. Ventilation is needed to remove heat and maintain oxygen levels as carbon dioxide is generated through respiration. Thus, ventilation holes must be provided in cartons. If cartons are stacked on pallets, ventilation pathways should not be obstructed. This requires stacking on the pallet to allow for airflow between cartons, or

careful design of the positioning of the air vents so that they line up under all stacking configurations.

Unfortunately, products also lose water during storage. This results in a loss in product mass, and sometimes shriveling. Packaging (especially plastic films) can be used to reduce this problem. A balance is required that allows for some gas transfer but reduces water loss to an acceptable level. The balance also may vary among cultivars.

Purposes of Packaging

There are four key purposes of packaging, as shown in the following subsections.

Containment

This is the basic function of packaging. The product must be contained so that it can be transported as required. Failure to contain the product leads to loss, damage, and pollution of the environment.

Protection

This is especially important for perishable and easily damaged products. The product must be protected from environmental effects, including water, undesirable moisture vapor, odors, microorganisms, dust, shock, vibration, and compression. The package also helps to reduce the risk of theft, willful damage, and contamination.

Apportionment and Convenience

The package enables the product to be divided up into convenient quantities so that it can be transported easily and distributed in sizes that suit the retailer or consumer. For long-distance transportation the primary packages must be designed so that they can be unitized, that is, grouped together so they can be transported as a single item such as a pallet load.

Communication

The package also must provide information about its contents. The package provides the ideal place to give the information needed for good quality management, with details about the crop, including variety, quantity of fruit, harvest date, origin, storage requirements, and grower identification. It can be also used for marketing purposes ('a package must protect what it sells and sell what it protects').

Containment: Types of Packing Configuration

Fruit can be arranged into cartons in various ways (see Fig. 3.19). Factors that should be considered include cost, need for atmospheric control or modification, need for protection from compression, impact or rubbing damage, and market and shipping size requirements.

Individual Wrappings

Fruit may be individually wrapped in tissue paper. The purpose is to protect the fruit during transportation (especially if the product is prone to rubbing damage), to provide an attractive look to the product, to control the atmosphere around the fruit (moisture, carbon dioxide, and oxygen) and possibly to provide a source of fungicide to reduce postharvest disorders, by impregnating the tissue with a suitable chemical (e.g., diphenyl for citrus).

Jumble Packing

The most common packaging worldwide is probably the jumble pack, in which fruit are placed inside a container at random without intervening cushioning material. This package is the simplest and least costly, in terms of material requirements and packing effort. However, it offers little protection to the product during transportation, and so damage levels can be high.

The container may be a cardboard carton, a sack, a plastic bag, or a traditional container woven from local materials. The features of this style of packaging are

- Simplicity
- Low cost
- Easy filling
- Low packing density
- Little protection for product from impact and compression
- Unattractive appearance to consumer
- Product normally measured by weight
- Readily handles odd-shaped and mixed-sized products
- Settling during transportation

Smaller fruits, such as strawberries and cherries, are usually jumble-packed. Although this may be acceptable for low-value products for the local market, it is not well suited to larger-sized high-value products destined for distant markets, especially if they are susceptible to mechanical damage.

Pattern Packs

For higher-valued produce, pattern packing systems should be considered. The product is placed in a regular configuration and is likely to have protective packaging to separate it from other fruit and provide the regular placement pattern. For products that have been sized and have a regular shape, fruit tray packs provide good positioning and protection. Each tray is shaped to contain an array of pockets, so that one fruit fits in each pocket. The next tray is placed on top, so that the fruit is positioned in a pocket formed by the underside of the upper tray. Fruit are therefore separated from fruit in the layer above and prevented from moving sideways to contact other fruit in the same layer. Trays can be made from paper pulp, plastic, or expanded foam (Fig. 3.20a).

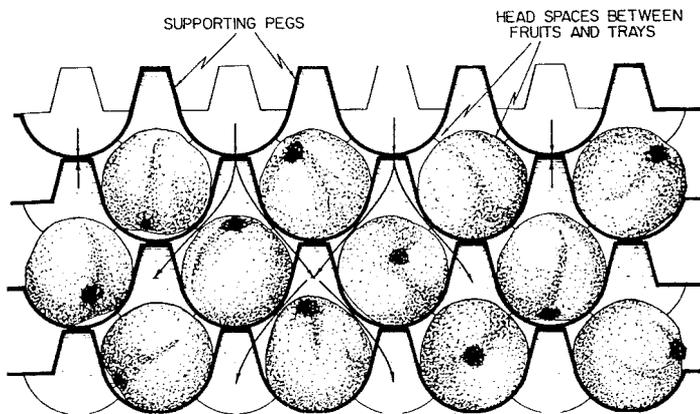
There are two distinct types of tray. In the design shown in Fig. 3.20a, the product supports the tray above. Depending on the design of the carton, the product also may support some of the weight of the cartons stacked on top (the pressure pack).

These packs are suitable for apples and pears. Two stacking arrangements are possible: an in-line arrangement (Fig. 3.20a), which results in each fruit being supported by only two fruit; and the face-centered cubic arrangement, in which each fruit is supported by four fruit (Fig. 3.21). The latter tray design provides cushioning through a “hammock” effect (Fig. 3.22).

Alternatively, the peg type is designed so that the product carries no load. Between each fruit the tray forms a column, which supports the tray above (see Fig. 3.20b). The product is free to move within the pocket. If transportation involves significant vibration the product may be damaged by rubbing (causing skin blemishes) or bruising.



(a)



(b)

Figure 3.20. Packaging. (a) Pressure-pack tray system. (b) Peg-type tray system (from [39]).

Paper pulp trays and expanded foam trays provide a significant cushioning effect to reduce impact damage [40]. Paper pulp readily absorbs moisture and helps to remove excess water from around the fruit. This softens the tray so that it molds more closely around the fruit.

Theoretical analyses, based on crystallography, give the maximum number of objects that can be put into a finite-sized container. Practical results depend upon the shape and uniformity of the product. Many products are spheroidal in shape (i.e., they have a circular cross-section in at least one plane, while in the other two orthogonal planes the cross-sections may be elliptical). Peleg [39] discussed the packing properties of identical

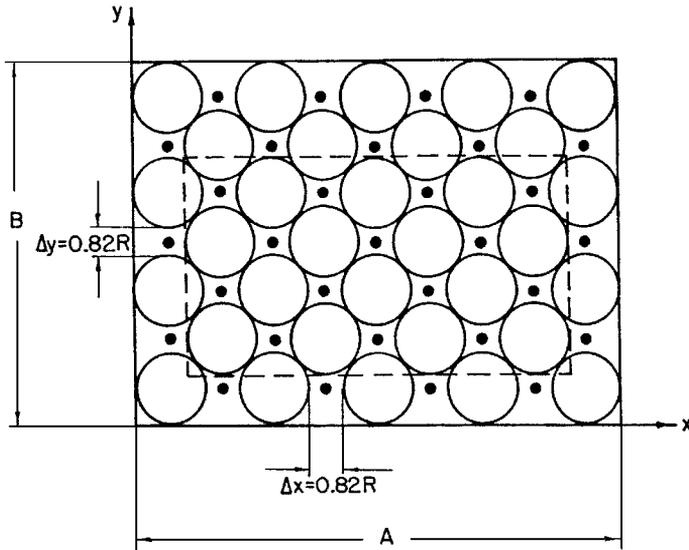


Figure 3.21. Plan of a face-centered cubic pattern pack of spheres. *Open circles indicate spheres in bottom layer; closed circles indicate spheres in second layer.* (Source: [39])

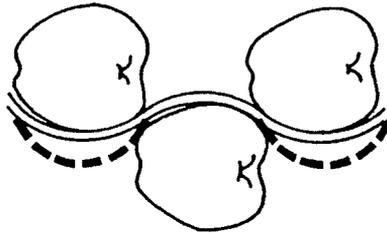


Figure 3.22. The "hammock" principle. The tray directs pressure downwards and away from the product, as shown by the broken lines. (Keyes Fiber Co., from [39])

spheroids. A key factor is the packing density, which is the ratio of the volume occupied by the fruit to the total volume of the package. Its value depends on the arrangement of the spheroids. The maximum value for an array of equal-sized spheres in an infinitely large box is 0.74. This occurs when the spheres are arranged in a face-centered cubic. In this arrangement, every sphere touches its 12 nearest neighbors, and the distance to the center of the next nearest nontouching sphere is 1.41 diameters. For finite-sized containers (with between 50 and 300 fruit) the maximum value of S is between 0.55 and 0.68. These values allow for space lost at the sides of the container.

Cell Packs

Each layer of a cell pack consists of pockets formed by vertical sheets of packaging material that separate the fruit. The sheets can form a square arrangement using straight pieces of interlocking cardboard, or a hexagonal honeycomb pack can be used in which the walls are formed from expanded paper honeycomb stock. For some fruits the cells can be arranged in a triangular pattern to suit the shape of the product. Plain paper or cardboard sheets separate each vertical layer in the container. The vertical walls can carry some stacking load, and so the cartons can be relatively inexpensive.

Protection

Shock, vibration, and static compression are the three loading situations that can cause damage to produce.

Shock

Studies of transportation systems have shown that packages receive many small shocks but few large shocks. Smaller packages tend to receive a greater number of large impacts (Fig. 3.23).

Handholds in the side of cartons reduce drop heights. Cautionary “fragile” labels appear to have only a small effect on the amount of mishandling a package receives. Cushioning against shock is an important function of packaging material. Cushioning aims to reduce the impact load by spreading the deceleration over a longer time period, keeping the g value ($1 g = \text{acceleration due to gravity} = 9.8 \text{ m s}^{-2}$) of the deceleration below the level at which the product will be damaged [41]. Ideally, the packaging material needs to be thick enough to recude the velocity to zero without bottoming out

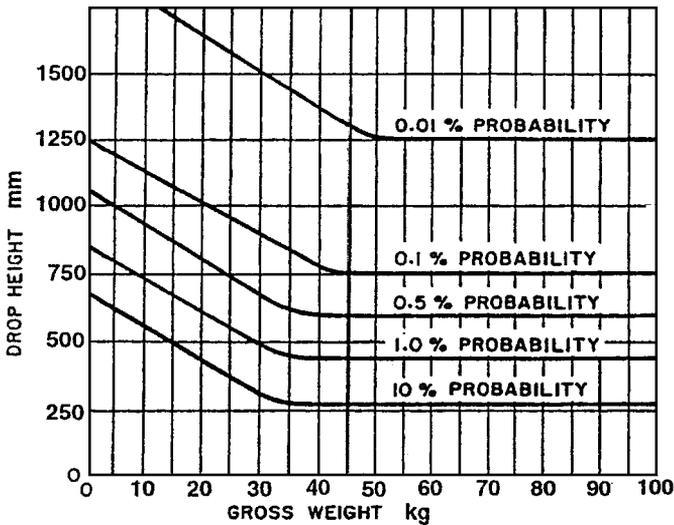


Figure 3.23. Drop-height probability curves. These are based on experimental observation. The curves flatten out as mechanical handling systems predominate. (Source: [41])

Table 3.22. Cushioning values

Material	Density (kg/m ³)	Typical Cushion Factor C (m/s ²)	Maximum Static Stress (kPa)
Flexible urethane foam ^a	30	2.2	1.5
Expanded polyethylene	45	2.6	10.8
Expanded polystyrene	16	3.1	13.7
Expanded polyethylene	37	3.2	66.9
Expanded ethylene vinyl acetate	50	3.5	3.9
Bonded polyurethane chipfoam	64	3.0	1.8
Bonded polyurethane chipfoam	96	3.0	2.5
Bonded polyurethane chipfoam	144	3.7	5.9
Bonded polyurethane chipfoam	192	4.1	9.8
Rubberized hair	32	3.2	1.0
Orientated rubberized hair: style CA	96	2.4	9.8
Orientated rubberized hair: style CA	64	2.5	6.9
Orientated rubberized hair: style CA/CA	96	2.6	11.8
Plain rubberized hair	64	3.6	1.5
Plain rubberized hair	96	4.3	2.9

Source: [42].

^a Likely to be more variable in performance than other materials listed.

(i.e., penetrating the cushioning layer). In theory, it is simple to calculate the thickness required. However, in practice, a thicker layer is necessary. Cushioning materials can be classified by a cushioning factor C (m/s²), defined by:

$$C = L \cdot G/H \quad (3.40)$$

where L is the required thickness of the cushioning material (m), G is the fragility factor of the product (the g value for failure) in meters per second squared, and H is the drop height (m). Cushioning values are listed in Table 3.22 [42]. Cushioning curves are preferred for cushioning calculations (Fig. 3.24). To use these the peak deceleration is required. The curve that crosses this value twice gives the thickness and range of acceptable static loads that can be supported (e.g., in Fig. 3.24, at 30 g, 75 mm thick material is acceptable from 500 to 2600 Pa). However, the optimum at the minimum of the curve is marked by the dotted line (1500 Pa).

Vibration

Vibrations up to 100 Hz can cause problems, particularly for fruit that has no packaging protection. Vibrations occur, in particular, during road shipment (Fig. 3.25). On trucks and trailers, air-suspension systems are generally preferable to spring-leaf suspensions. Resonance problems also can cause major difficulties. For very delicate products, packaging may need to be designed to avoid stack resonance conditions. Usually this is not a serious concern for fresh produce, but it might be for long-term low-frequency vibrations in ship holds.

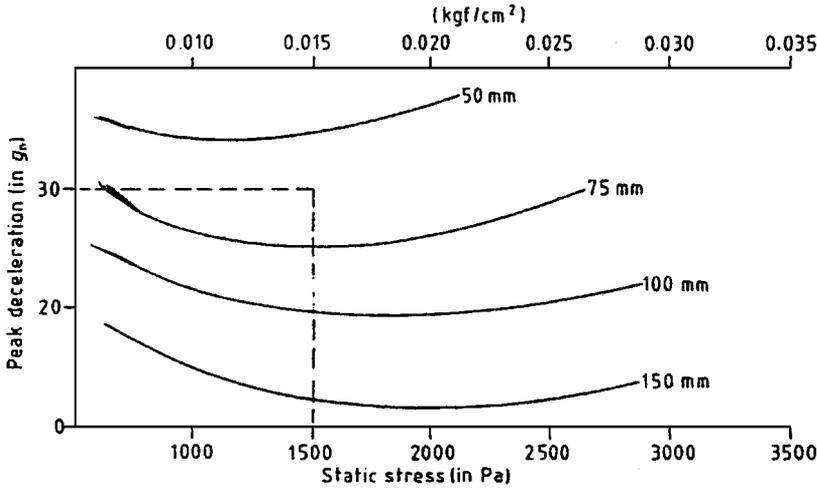


Figure 3.24. An example of a dynamic cushioning curve. (Source: [41]).

Static Compression

It is likely that product will be stacked for transportation and storage. The stack height usually is limited only by the space available, unless clear stack-height limits are set by the industry. For some fruits (e.g., apples) the package can be designed to allow the fruit to support a significant part of the static stacking load without damage to the product (impact loads during handling are much greater than the static compression forces).

However, problems can arise in cool stores, especially if the humidity is high, as cardboard loses strength as it absorbs moisture. The design strength also is reduced if the stack is not packed with the sides in perfect alignment (Fig. 3.26 and 3.27). Standard design procedure is to halve the design strength of corrugated cardboard cartons for non-perfect stacking arrangements, halve it again after 12 months of cool storage, and halve it again in high humidity conditions (90%). The carton strength (CS_T) is determined from:

$$CS_T = CS_L K_{RH} K_T K_{SP} \tag{3.41}$$

where CS_L is the strength measured at 23°C and 50% relative humidity, and K_{RH} , K_T , and K_{SP} are the relative humidity, time, and stacking factor corrections given in Tables 3.23 and 3.24. Handholds also reduce the strength of packages by as much as 20%.

If cartons are stacked too high, or in an irregular style so that the corners do not line up properly, carton failure may cause the stack to lean or topple, resulting in excessive damage to the product. In some cool stores, timber props are used to provide additional carrying support for multiple layers of pallets. Problems also can occur if cartons are overfilled, or if the fruit is not sufficiently protected with cushioning between each fruit.

On pallets, the strength of the cartons are substantially reduced if the cartons are not stacked carefully, or if one pallet is stacked on another incorrectly (see Fig. 3.26; Table 3.24).

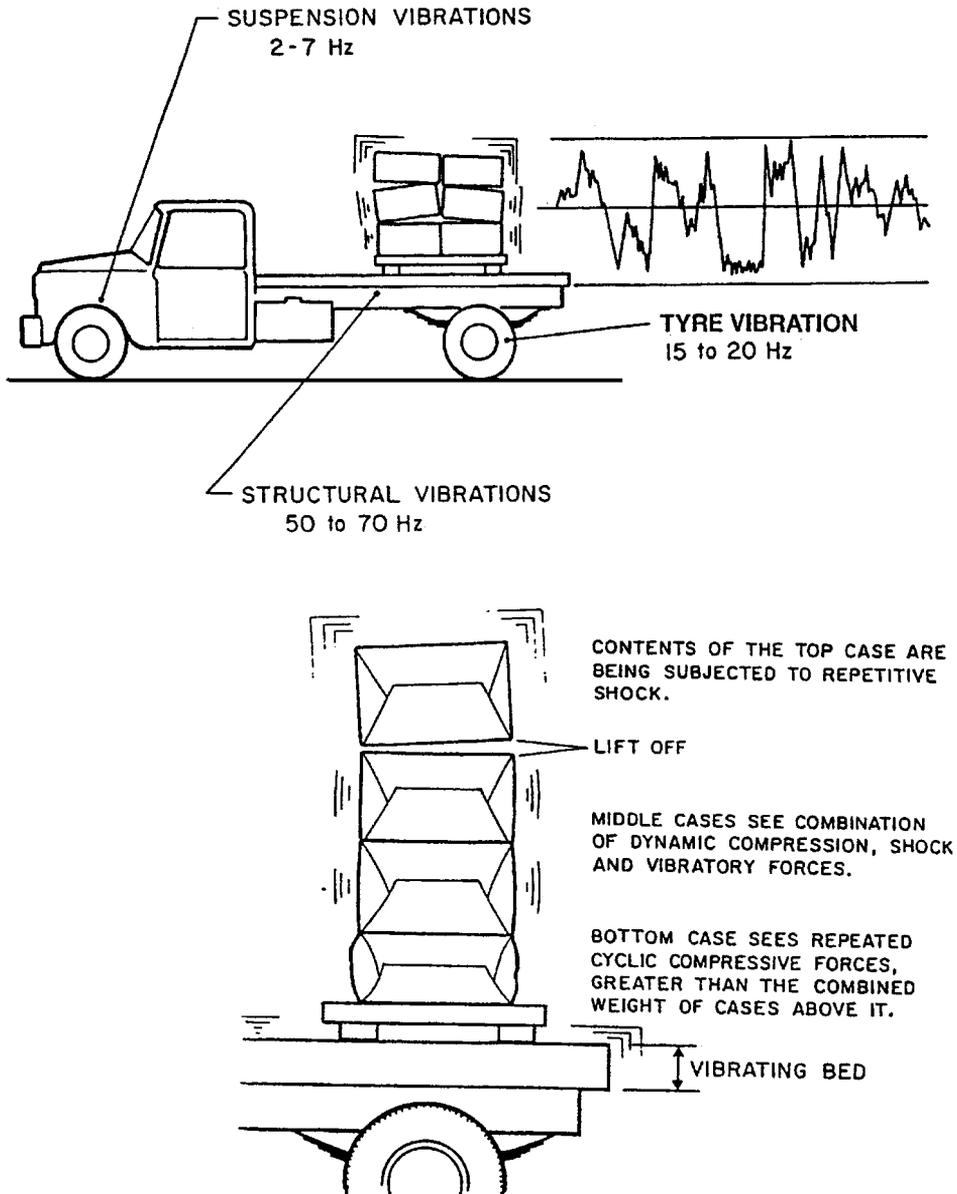


Figure 3.25. Typical sources of vehicle bed vibrations. (Source: [41])

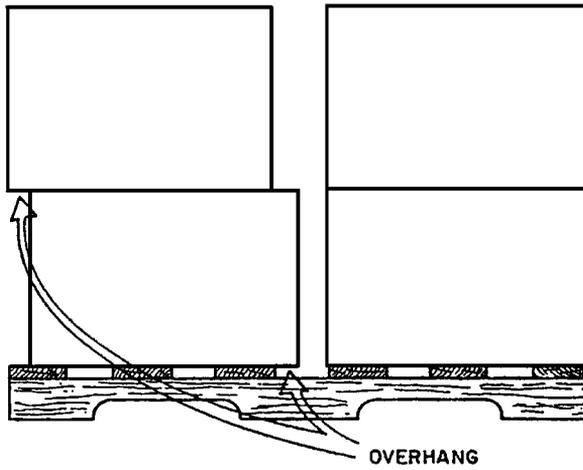


Figure 3.26. Effect of overhang on compression stack strength (see Table 3.23). (Source: [41])

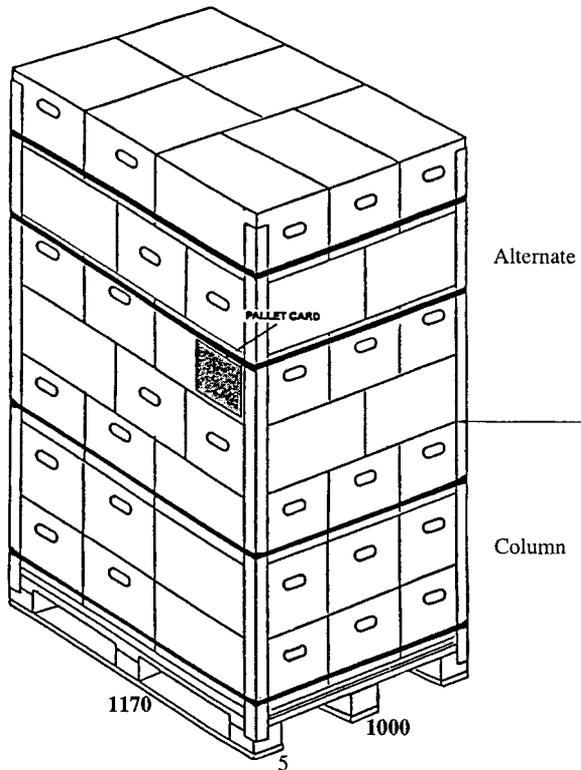


Figure 3.27. A typical pallet of cartons (Enzafruit). The bottom three rows are “perfectly” stacked to give maximum strength (see Table 3.22).

Table 3.23. Strength-correction factors for corrugated boxes (changes from values at 50% humidity, 23°C)

Load Duration	K_T (%)	Relative Humidity	K_{RH} (%)	Alignment	K_{SP} (%)
Short-term	100	Dry	125	Perfect	100
10 d	65	25	110	Offset	50
30 d	60	50	100		
100 d	55	75	80		
365 d	50	85	60		
		90	50		

Source: ASTM D-642 (see [41]).

Table 3.24. Effect of overhang on compression stack strength

Amount of Overhang (mm)	Loss (%)
25 on one side	14–34
50 on one side	22–43
25 on one end	4–28
50 on one end	9–46
25 on one side and one end	27–43
50 on one side and one end	34–46

Apportionment, Convenience, and Labeling of Cartons

After primary packaging is completed, produce is unitized into containers that can be handled conveniently. Cardboard cartons with a maximum weight of up to 20 kg are common for many fruit. However, in some markets smaller weights are preferred. A carton can be labeled conveniently to identify the product and is easy to stack. The carton can be used for the entire postharvest chain, at least to the retailer. The carton can be printed with marketing slogans and other information. The dimensions of the carton should be such that it fits a standard pallet.

With the advent of supermarket chains, carton sizes need to be selected to suit the display requirements of the retailer. Typically, a retail display pack for the European market measures 600 by 400 mm and is no more than 150 mm high with one or two layers of fruit. Cartons of this size fit exactly into the display stands of many major supermarkets and can be fitted onto a standard pallet.

The design of tray packs requires careful thought. Trays should be designed to suit the particular product, and different designs are required to accommodate the range of product sizes normally encountered. On the international market, standardization of package sizes and palletization place limits on the acceptable sizes and dimensions of cartons. It is difficult to optimize the design of cartons to provide one size of a fixed weight for a range of fruit sizes. In practice standard configurations can be developed, giving a limited set of fruit sizes. Cartons may then be identified by the number of fruit contained. Thus a count-100 carton represents a carton containing 100 fruit. Examples of carton layouts are shown in Fig. 3.20.

Carton designs vary. Common options for fruit include the standard slotted container (in which the lid is made up of four flaps attached to the sides which fold over), the telescopic carton (in which the lid is a separate box that completely encloses the sides of the carton), or combinations of timber and cardboard. Telescopic designs are suitable for long-term storage. Some retail display cartons are designed to be without a lid. The cover is provided by the base of the carton on top of the pallet. These designs require lugs on the sides to ensure that they are accurately located over the walls of the lower carton, and to eliminate sideways movement.

Cartons also can be designed to accept bags of fruit for unitization purposes. These secondary packages may be large enough to sit on a whole pallet. Cell dividers can be used to separate individual bags of fruit.

Palletization

Increasingly, palletization is being used to simplify international handling systems. Cartons are loaded onto wooden pallets that consist of a raised flat base designed to allow the forks of a forklift truck to slide underneath for easy lifting and moving. Product must be shipped on standard-sized pallets, which are designed to fit into ship and aircraft holds, as well as in road and rail systems. The European standard is 1200 by 1000 mm. Ship cargo holds limit the height of a full pallet to 2.2 m, so the carton dimensions are limited to set multiples, unless the shipper is prepared to accept wasted cargo space. A carton with outer dimensions 499 by 329 mm and 285 mm high can stack seven layers high on a pallet in the form shown in Fig. 3.27. However, stacking cardboard cartons to the full height of the hold is only possible if the carton is designed to withstand the loads under high-humidity and low-temperature conditions, and if the cartons are properly packed so that the sides are well supported.

Pallets of cartons are assembled at the packing shed, and the pallet load may then receive additional packaging in the form of plastic shrink wrapping, banding, or edge strengtheners. The product is handled in this form at least as far as the wholesale market.

3.3.5 Reducing Handling Damage in the Postharvest Chain

Every stage in a handling chain is a risk area for product damage. Good design, coupled with regular maintenance of equipment, helps to reduce problems. In addition, good management, staff training, and the adoption of procedures to minimize the risk of damage are vital.

System and Machinery Design to Reduce Damage

All fruit- and vegetable-handling equipment should be designed to minimise damage. Machinery must be designed to avoid blockage or build-up of product. This requires that each section of a grading machine be designed to match the other components. The flowrate of product through a machine is a critical variable. This should be adjusted to suit the product so that damage is minimized.

It is particularly important to avoid high impact loads, particularly against other product. Long drops and chutes should be avoided. If changes in height must be built into a grading machine, product velocity-control or velocity-reduction systems are needed, especially if the product rolls easily (e.g., Fig. 3.16). This can be achieved by hanging

flaps over chutes, but these tend to cause blockages if product size and shape vary. Pockets on transfer conveyers are a more positive system. Horizontal product transfer can be facilitated with power-driven overhead brushes, which sweep the product gently at a controlled speed in the desired direction.

Conveying machines to fill large bins are available commercially. These are designed so that the product is transported to the chute outlet at a controlled rate and delivered just above the product already in the bin. The chutes on these machines move sideways so that filling is even across the bin.

Machinery Maintenance

Handling and grading equipment can cause significant damage if it is not maintained properly. The most common deficiencies are wear of cushioning materials at critical points and timing faults at transfer points between one component of a machine and another. Cushioning should be checked daily, particularly at transfer points, and replaced frequently. Often dirt can build up in the material, which reduces its effectiveness as a cushion. Timing between singulators and weighing cups is critical for grading machines for single fruit such as apples and pears, and these should also be monitored closely for signs of problems. Machinery should be given a thorough overhaul before the start of the season, and cushioning should be renewed throughout the machine. Performance should be monitored carefully, particularly at the start of the season. Handling machinery can behave differently when fully loaded with fresh fruit or vegetables, compared with operation with only a few samples from the previously season passing through.

Staff Training

Because much of the damage to fruit and vegetables is latent, workers can be unaware that they are causing damage. Regular training helps to keep awareness levels high. When problems arise, these need to be corrected. Good management practices help. For example, paying staff by the quantity of product picked is an encouragement to work too fast, resulting in excessive damage. Poor supervision and long working hours also encourage poor handling practices. Total quality management systems should be adopted. These encourage staff involvement in quality improvements. It is essential that in every part of the chain a consistent approach is maintained: Pickers will see little point in being careful if packers mistreat fresh products.

Fruit and vegetables are most susceptible to damage when they are transferred. Forklift operators should be made aware of the need for careful handling. After products are packaged the risk of damage still remains, and the tendency for staff to believe that the product cannot be damaged inside a package should be corrected. Drop tests on apple cartons showed that a 600-mm drop can result in damage to 70% of the fruit, even if paper-pulp tray dividers are used [23].

Reducing Bruise Susceptibility

Some products can be handled more easily if handling is delayed after harvest. Potatoes, taro, apples and onions are examples. There is some evidence that fruit handled cold will be slightly more bruised than fruit handled at room temperature [24, 32, 35].

There are conflicting research results on the effects of storage times and fruit maturity on handling damage susceptibility (e.g., see Tables 3.19 through 3.21). The direction of the change appears to depend on the variety [32, 43]. Turgor pressure and tissue strength can affect bruising in apples independently. High turgor pressure increases the amount of bruising. Factors that cause an increase in turgor pressure include harvesting early in the day and increased maturity of fruit. Factors that reduce turgor pressure include water loss, or length of storage time. Lower turgor pressure probably reduces bruise susceptibility, because impact forces are reduced. Unfortunately, this has to be balanced with customer preferences for fresh, high-turgor fruits and vegetables.

Although maturity and size affect bruising during handling, rainfall prior to harvest, time of day of picking, and storage conditions are recognized by commercial growers as factors that affect bruising levels [31].

Another factor is the structure of the fruit. Large cells or cells that are under greater stress are more likely to be damaged by mechanical loading than smaller cells. Khan and Vincent [44, 45] found that apple texture in some cultivars is anisotropic, and that cells close to the core of the apple have different mechanical properties than cells nearer the skin. Thus, there are a number of geometrical factors that need to be considered for a complete understanding of product damage.

Factors that change cell-wall strength and stiffness alter bruising susceptibility. Positive factors include calcium levels in the fruit; negative factors include product age and poor storage conditions. The small increase in bruising occurring at low temperatures may occur because cell walls become less flexible at low temperature, as indicated by twist-test measurements [46].

In storage, bruising may diminish or increase depending on whether the effects due to loss of turgor pressure are balanced by the loss in cell-wall strength [32, 43].

3.3.6 Identification of Problem Areas in Handling Systems

Frequently it is possible to identify problem points in a handling chain. For apples, damage increases steadily as fruit progresses along the handling chain [47–51]. The worst problems in the orchard occur when fruit are placed into field bins from picking buckets. Cushioned field bins, combined with special techniques to avoid forming a pile of fruit inside the bin, help reduce problems. In grading sheds, most bruising occurs when fruit falls from the weighing cups onto other apples in final size bins and at the singulator on some grading machines (but not all). Pang *et al.* [52] found that fruit-to-fruit impact could be a major cause of damage. High- and low-damage points in apple handling systems are listed in Table 3.25.

In order to identify problem areas the options are either to conduct a series of experiments using a large sample of fruit or to use a suitable device to assess loading damage. Survey techniques can be slow, especially if a fault occurs in the middle of the season. The procedure requires that a sample of about 100 fruit be passed over each point considered as a potential problem. A control sample of the same number should be placed in the machine and removed without passing through the section under test to eliminate extraneous handling effects during the test. Once the damage has developed

Table 3.25. High and low damage areas (New Zealand apple handling systems)

Potentially High Level of Damage	Low Level of Damage
Picker transferring fruit into larger field bin	Finger bruising by pickers
Transport out of field in field bin	
Dry dump (i.e., no water dump)	Water dump
Grader transfer points	
Drop onto grading table	Grading table
Drop onto singulator	Velocity-control brushes
Timing and uncushioned surfaces at transfer wheel to cups	Cushioned channels and dividers
Cup drop onto chute if cushioning is worn	Cup drop onto chute if cushioning is not worn
Final run into final size bins (fruit–fruit impact)	Automatic tray fillers (no chutes)
Excessive speed	After packaging
Long chutes	

Source: [47].

to the extent where it is visible, an assessment can be made. This procedure is far from straightforward, as additional problems arise in obtaining a suitable sample of fruit. An alternative approach is to use an “electronic fruit” that records loads and impacts as it passes through the handling system.

Electronic Fruit

Several electronic devices have been developed worldwide. The most widely used is the American Instrumented Sphere, which consists of a triaxial accelerometer mounted inside a molded plastic ball, designed so that the output from the accelerometer is recorded on a microcomputer embedded inside the sphere [33, 53–55]. The output from the accelerometer is monitored continuously, but the data are saved only each time the acceleration exceeds a threshold level. The sphere is powered by rechargeable batteries. Information on each impact is collected and downloaded onto a computer for detailed analyses. The Instrumented Sphere is a few centimeters in diameter; larger sizes are available. It records only impact loads, and has an operational life of a few hours before recharging is needed. Information provided includes the maximum acceleration, the velocity change (i.e., the area under the acceleration–time curve), and the time of each event. If the progress of the sphere is monitored with a video camera, the location of each significant event can be identified. In assessing a handling system, the sphere normally is passed through the system several times so that potential problem areas are identified. Studies have been conducted on citrus, apples, squash, pears, and potatoes. The output (acceleration and velocity change) has to be interpreted in terms of damage done to real fruit.

An electronic potato has also been developed [56]. This device has a piezoelectric surface layer, covered with appropriate materials to enable the sphere to have similar properties to the fruit or vegetable it simulates. The sphere records the time and relative severity (on a scale from 0 to 7) of the worst impact measured during a run [56]. This sphere has the advantage that the user need not conduct laboratory assessments to correlate the output with the damage. A pressure sphere has been developed that has a rubber surface and measures the changes in pressure in a hydraulic fluid inside the sphere [57].

This device can measure both impact and static pressures and is durable under rough handling conditions.

Explanation of Output of Instrumented Sphere

Data from the Instrumented Sphere is downloaded, and peak acceleration and velocity change from each recorded impact can be studied in sequence for problem diagnosis. The results can be presented as a graph of peak acceleration against velocity change (Fig. 3.28). For diagnosis, various curves are drawn on the graph; the lowest curve indicates impacts against a solid surface such as steel; other curves indicate surfaces that are partly cushioned.

The acceleration is proportional to the maximum force generated during an impact recorded by the sphere. The velocity change gives an indication of the type of impact (see Fig. 3.19). A low velocity change indicates that the impact occurred against a hard material, whereas a large velocity change at the same maximum acceleration indicates an impact against a soft material.

This means that if the sphere strikes a steel surface the resulting impact is close to the steel line. If it strikes a cushioned surface, the impact is well above this line, depending on the nature of the cushioned surfaces. The resulting impact lies in the zone marked Y. High peak acceleration values are required to cause bruising. If the sphere strikes a fruit, the impact is in the zone labelled Z. These impacts can cause fruit damage, even though the acceleration is low and the velocity change high [55]. There can be some ambiguity in this region, as it is possible to obtain an impact in the same region from a gentle impact on a soft cushioned surface. However, use of a video camera enables the

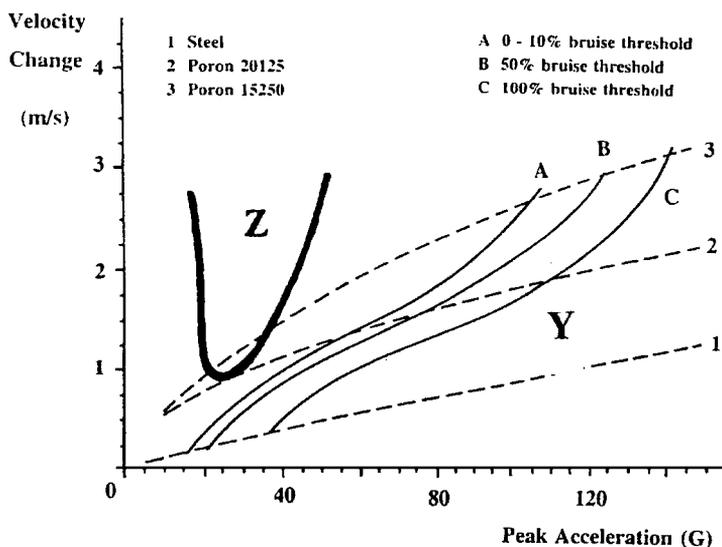


Figure 3.28. Apple-bruising initiation threshold lines showing 0%–10% (A), 50% (B), and 100% (C) bruising probability for impacts against steel and cushioning materials (zone Y) [53, 54]. The figure also shows the region in which fruit to fruit impacts are recorded (zone Z). Bruises can occur in this zone [55].

Table 3.26. Damage thresholds of varieties of apples for various impact surfaces ($m/s^2 \times 9.81$)

	Splendour	Gala	Fuji	Braeburn	Granny Smith
Steel	65	79	61	84	65
Rubber	59	54	56	77	59
Tube	48	—	40	64	45
Bar	40	56	—	—	—
Fruit	21	26	22	33	21

Source: [55].

object struck to be identified positively. Impacts against uncushioned surfaces such as plastic rollers or nonrigid metal components produce curves as indicated in Fig. 3.28. The threshold for damage is at a higher peak acceleration level than for steel, but less than on cushioned surfaces.

A key component of the diagnosis is a knowledge of the threshold of damage for a product. Damage thresholds not only depend on the fruit or vegetable type and cultivar, but also on the type of surface. Threshold curves have been obtained for a range of products and cultivars from laboratory experiments. Thresholds can be determined as the lower limit for zero damage. Alternatively, thresholds can be set in terms of the probability of fruit damage, or of damage above a commercially significant size [54]. Typical results are given in Table 3.26 for threshold levels causing bruising in apples.

List of Symbols

A	bruise surface area (m^2)
a	radius of contact area (m)
b	bruise susceptibility (m^3/J)
B_{AS}	bruise area susceptibility ($m^2/J^{3/2}$)
B_{CS}	commercial bruise susceptibility ($m^2/J^{3/2}$)
B_P	bruise visibility factor
C	cushioning factor ($m\ s^{-2}$)
CS_T	carton strength in storage (N)
CS_L	carton strength at 23° and 50% RH (N)
d	surface diameter of bruise (m)
ΔE	energy loss (J)
E	impact energy (J)
E'	dissipated energy (vibrations etc) (J)
E_0	initial energy (J)
E_{abs}	absorbed energy (J)
E_{Reb}	rebound energy (J)
E_R	rotational energy (J)
e	coefficient of restitution
ϵ	strain
F	applied force (N)
F_m	magness Taylor penetrometer force (N)
G	fragility factor ($m\ s^2$)

g	acceleration due to gravity ($9.81 \text{ m} \cdot \text{s}^{-2}$)
h	bruise depth at centre (m)
H	drop height (m)
I	inertia ($\text{kg} \cdot \text{m}^2$)
K_1	empirical constant - equation (3.39)
K_{RH}, K_T, K_{SP}	Relative Humidity, time, and stacking factor correction factors for corrugated cardboard containers (%)
k	material constant defined in Eq (3.23)
L	thickness of cushioning material (m)
M, M_1, M_2	mass (kg)
n	constant defined in Eq (3.35)
P_{\max}	maximum pressure on contact area (Pa)
Q	angular rotation ($\text{rad} \cdot \text{s}^{-1}$)
R, R_1, R_2	radii of curvature in contact area (m)
R_{1A}, R_{1B}	orthogonal radii of curvature of surface 1 etc.
r	radius of sphere (m)
σ	stress (Pa)
S	packing density
T	momentum (N s)
t	time (s)
U	initial velocity before impact ($\text{m} \cdot \text{s}^{-1}$)
U'	velocity after impact ($\text{m} \cdot \text{s}^{-1}$)
u	velocity ($\text{m} \cdot \text{s}^{-1}$)
V_b	bruise volume (m^3)
V_s	volume of compression sample (m^3)
ν	Poisson's ratio of the material
X	bruise height above contact plane (m)
x	closest approach distance (m)
Y	Young's modulus of elasticity (Pa)

References

1. Burden J., and R. B. H. Wills. 1989. Prevention of food losses: Fruits, vegetables and root crops: A training manual. FAO training series No. 17/2. Rome: United Nations Food and Agriculture Organisation.
2. American National Research Council. 1978. *Report of the Steering Committee for Study on Postharvest Food Losses in Developing Countries*. Washington, DC: National Science Foundation.
3. Amuttiratana, D., and W. Passornsiri. 1992. Postharvest losses in Thailand. In *Postharvest Losses of Vegetables*, ed. M. H. Bhatti, C. A. Hafeez, A. Jaggar, and C. M. Farooq. Workshop report, Oct. 1992, Islamabad, FAO publication RAS/89/41.
4. Thompson, A. K. 1996. *Postharvest Technology of Fruit and Vegetables*. Oxford: Blackwell.

5. Kitinoja, L., and A. A. Kader. 1995. Small-scale postharvest handling practices, 3rd ed. Postharvest Horticulture Series No. 8, Department of Pomology, University of California, Davis.
6. Studman, C. J. Ergonomics in apple sorting: A pilot study. *Journal of Agricultural Engineering Research* 70:323–334.
7. Pheasant, S. T. 1988. *Bodyspace: Anthropometry, Ergonomics and Design*. London: Taylor and Francis.
8. Nicholas, J. V. 1985. Colour and light for the inspection table. Sirtec Publication No. 1, Department of Scientific and Industrial Research, Wellington, New Zealand.
9. Brown G. K., D. Marshall, and D. Timm. 1993. Lighting for fruit and vegetable sorting. Conference Proceedings, Fourth International Symposium on Fruit, Nut and Vegetable Production, paper 935.13, Valencia.
10. Shewfelt, R. L., and S. E. Prussia, eds. 1995. *Postharvest Handling: A Systems Approach*. San Diego: Academic Press.
11. Rodriguez, L., M. Tuiz, and M. R. de Felipe. 1990. Differences in structural response of granny smith apples under mechanical impact and compression. *J. Text. Stud.* 21(2):155–164.
12. Vamos-Vigyazo, L. 1981. Polyphenol oxidase and peroxidase in fruits and vegetables. *CRC Critical Reviews of Food Science* 15:49–127.
13. Davie, I. J. 1997. Role of calcium and mechanical damage in the development of localised premature softening in coolstored kiwifruit. Ph.D. diss., Massey University, New Zealand.
14. Hung, Y.C. 1993. Latent damage: A systems perspective. In *Postharvest Handling: A Systems Approach*, eds. R. L. Shewfelt, and S. E. Prussia, chapter 10. San Diego: Academic Press.
15. Ouyang, L., and C. J. Studman. 1997. Bruise measurement by image analysis. Conference Proceedings, Fifth International Symposium on Fruit, Nut and Vegetable Production, University of California, Davis.
16. Klein, J. D. 1987. Relationship of harvest date, storage conditions, and fruit characteristics to bruise susceptibility of apple. *Journal of the American Society of Horticultural Science* 112(1):113–118.
17. Mohsenin, N. N. 1986. *Physical Properties of Plant and Animal Materials*, 2nd ed. New York: Gordon and Breach.
18. Holt, J. E., and D. Schoorl. 1977. Bruising and energy dissipation in apples. *Journal of Texture Studies* 7:421–432.
19. Schoorl, D., and J. E. Holt. 1980. Bruise resistance measurements in apples. *Journal of Texture Studies* 11:389–394.
20. Chen, P., and Z. Sun. 1981. Impact parameters related to bruise injury in apples. *American Society of Agricultural Engineers*, paper 81–3041. St Joseph, MI: ASAE.
21. Kader, A. A. 1983. Postharvest quality maintenance of fruits and vegetables in developing countries. In *Postharvest Physiology and Crop Production*, pp. 455–470. New York: Plenum.

22. Studman, C. J. 1994. Quality in Fresh Fruit: Meaning, Measurement and Maintenance. Proc. AGENG'94 Milan, Italy. Paper 94-G-067.
23. Heap, R. A. 1994. Performance of recycled paper pulp trays in relation to impact damage in apple cartons. Master's thesis, Department of Agricultural Engineering, Massey University.
24. Pang, D. W., C. J. Studman, N. H. Banks, and P. H. Baas. 1996. Rapid assessment of the susceptibility of apples to bruising. *Journal of Agricultural Engineering Research* 64:37–48.
25. Siyami, S., G. K. Brown, G. J. Burgess, J. B. Gerrish, B. R. Tennes, C. L. Burton, and R. H. Zapp. 1988. Apple impact bruise prediction models. *Transactions of the American Society of Agricultural Engineers* 31:1038–1046.
26. Bollen, F., and B. T. Dela Rue. 1994. Assessment of damage in the apple postharvest handling system. Conference on Engineering in Agriculture, Australian Society of Agricultural Engineers, New Zealand, paper 94/012.
27. Roudot, A. C., F. Duprat, and C. Wenian. 1991. Modelling the response of apples to loads. *Journal of Agricultural Engineering Research* 48:249–259.
28. Studman, C. J., and N. H. Banks. 1989. Indenter shape effects in the impact bruising of apples and nashi. Conference Proceedings, Paper A14, 4th International Conference on the Physical Properties of Agricultural Materials, Rostock, East Germany.
29. Studman, C. J., and N. H. Banks. 1989b. The measurement of bruise susceptibility in apples and nashi. Conference proceedings, International Symposium on Agricultural Engineering, vol. 3, pp. 31–36.
30. Timoshenko, S. P., and J. N. Goodier. 1970. *Theory of Elasticity*, 3rd ed. New York: McGraw-Hill.
31. Mowatt, C. M. 1997. Reduction of bruising in apples. Ph.D. diss., Massey University, New Zealand.
32. Studman, C. J. 1997. Factors affecting the bruise susceptibility of fruit. In *Proceedings of Conference on Plant Biomechanics 1997*, ed. G. Jeronimidis, and J. F. V. Vincent. Reading: University of Reading.
33. Hyde, G. M. 1997. Bruising: Impacts, why apples bruise, and what you can do to minimize bruising. *Treefruit Postharvest Journal Washington State University* 8(4):9–12.
34. Kuang, M. 1998. Evaluation of alternative methods of bruise measurements in apple fruit. Master's thesis, Massey University, New Zealand.
35. Bollen, F., and B. T. Dela Rue. 1994. Assessment of damage in the apple postharvest handling system. Conference on Engineering in Agriculture, Australian Society of Agricultural Engineers, New Zealand, paper 94/012.
36. Mowatt, C. M., and N. H. Banks. 1994. Factors influencing the bruise susceptibility of apples. Final project report to the New Zealand Apple and Pear Marketing Board, Hastings, New Zealand.
37. Johnson, K. L. 1985. *Contact Mechanics*. New York: Cambridge University Press.
38. Dela Rue, B. 1996. A hierarchical modelling procedure to determine factors in apple bruising. Postharvest '96 Conference proceedings, Taupo, New Zealand.

39. Peleg, K. 1985. *Produce Handling, Packaging and Distribution*. Westport, CT: AVI Publishing.
40. Holt, J. E., D. Schoorl, and C. Lucas. 1981. Prediction of bruising in impacted multilayered apple packs. *Transactions of the American Society of Agricultural Engineers* 24:242–247.
41. Soroka, W. 1996. *Fundamentals of Packaging Technology*. Herndon, VA: Institute of Packaging Professionals.
42. British Standards Institute. 1992. Packaging Standards BS1133: Section 12.
43. Garcia, J. L., M. Ruiz-Altisent, and P. Barriero. 1995. Factors influencing mechanical properties and bruise susceptibility of apples and pears. *Journal of Agricultural Engineering Research* 61:11–18.
44. Khan, A. A., and J. F. Vincent. 1990. Anisotropy of apple parenchyma. *Journal of Science in Agriculture* 52:455–466.
45. Khan, A. A., and J. F. Vincent. 1993. Anisotropy in the fracture properties of apple flesh as investigated by crack opening tests. *Journal of Materials Science* 28:45–51.
46. Studman, C. J., and L. Boyd. 1994. Measurement of Firmness in Fruit and Vegetables. Proc. AGENG'94 Milan, Italy. Paper 94-G-066.
47. Banks, N. H. 1991. Identification of sources of bruises on Hawkes Bay grading equipment. Project report to New Zealand Apple and Pear Marketing Board, Massey University, New Zealand.
48. Schulte, N. L., E. J. Timm, G. K. Brown, D. E. Marshall, and C. L. Burton. 1990. Apple damage assessment during intrastate transportation. *Applied Engineering in Agriculture* 6:753–758.
49. Schulte, N. L., E. J. Timm, P. A. Armstrong, and G. K. Brown. 1991. Apple bruising: A problem during hand harvesting. Proceedings of the American Society of Agricultural Engineers, paper no. 91-1021.
50. Brown, G. K., C. L. Burton, S. A. Sargent, N. L. Schulte Pason, E. J. Timm, and D. E. Marshall. 1987. Apple packing line damage assessment. Proceedings of the American Society of Agricultural Engineers, paper no. 87-6515.
51. Jones C. S., J. E. Holt, and D. Schoorl. 1991. A model to predict damage to horticultural produce during transport. *Journal of Agricultural Engineering Research* 50(4):259–272.
52. Pang D. W., C. J. Studman, and G. T. Ward. 1992. Bruising damage in apple-to-apple impact. *Journal of Agricultural Engineering Research* 52:229–240.
53. Zapp, H. R., E. Ehlert., G. K. Brown, P. P. Armstrong, and S. S. Sober. 1990. Advanced instrumented sphere (IS) for impact measurements. *Transactions of the American Society of Agricultural Engineers* 33:955–960.
54. Tennes, B. R., H. R. Zapp, D. E. Marshall, and P. R. Armstrong. 1990. Apple handling impacts data acquisition and analysis with an instrumented sphere. *Journal of Agricultural Engineering Research* 47:269–276.
55. Pang, W., C. J. Studman, and N. H. Banks. 1992. Analysis of damage thresholds in apple-to-apple impacts using an instrumented sphere. *New Zealand Journal of Crop and Horticultural Science* 20:159–166.

56. Anderson, G. 1990. The development of artificial fruits and vegetables. Proceedings of International Conference on Agricultural Mechanisation, Zaragoza, 2:133–13.
57. Herold, B., I. Truppel, G. Siering, and M. Geyer. 1996. A pressure measuring sphere for monitoring handling of fruit and vegetables. *Computers and Electronics in Agriculture* 15(1):73–88.

3.4 Cold-Storage Systems

J. F. Thompson

3.4.1 Purpose of Storage

Orderly marketing of perishable commodities often requires storage to balance day-to-day fluctuations between product harvest and sales; for a few products, long-term storage is used to extend marketing beyond the end of harvest season. Long-term storage is feasible only if the product gains enough value during the storage period to pay for the cost of storage. To minimize product quality loss the storage must slow biological activity of product by maintaining the lowest temperature that will not cause freezing or chilling injury and by controlling atmospheric composition; slow growth and spread of microorganisms by maintaining low temperatures and minimizing surface moisture on the product; reduce product moisture loss and the resulting wilting and shrivel by reducing the difference between product and air temperatures and maintaining high humidity in the storage room; and reduce product susceptibility to damage from ethylene gas. With some commodities, the storage facility also may be used to apply special treatments. For example, potatoes and sweet potatoes are held at high temperature and high relative humidity to cure wounds sustained during harvest, table grapes are fumigated with sulfur dioxide to minimize *Botrytis* decay damage, and pears and peaches may be warmed and exposed to ethylene to ripen more quickly and uniformly. This section describes the equipment and techniques commonly used to control temperature, relative humidity, and atmospheric composition in a storage facility [1, 2].

3.4.2 Storage Considerations

Temperature

The temperature in a storage facility normally should be kept within about 1°C of the desired temperature for the commodities being stored. For storage very close to the freezing point, a narrower range may be needed. Temperatures below the optimum range for a given commodity may cause freezing or chilling injury; temperatures above it shorten storage life. In addition, wide temperature fluctuations can result in water condensation on stored products and also more rapid water loss. Recommended temperatures and humidities for long-term storage of horticultural products are shown in the Appendix, Table 3.A3. In many stores, particularly at wholesale and retail marketing, many products are held in the same cold storage. Table 3.27 groups commodities into four temperature and humidity groups for short-term storage.

Table 3.27. Compatible fresh fruits and vegetables during 7-day storage

	Vegetables				Fruits AND Melons			
	Group 1A (0–2°C, 90%–98% Relative Humidity)	Group 2 (7–10°C, 85%–95% Relative Humidity)	Group 3 (13–18°C, 85%–95% Relative Humidity)	Group 1B (0–2°C, 85%–95% Relative Humidity)	Group 2 (7–10°C, 85%–95% Relative Humidity)	Group 3 (13–18°C, 85%–95% Relative Humidity)	Group 3 (13–18°C, 85%–95% Relative Humidity)	
Alfalfa sprouts	Chinese cabbage	Mint	Basil	Apple	Prune	Avocado: unripe	Lime ^a	Atemoya
Amaranath	Chinese turnip	Mushroom	Beans: snap, green, wax	Apricot	Quince	Babaco	Limequat ^a	Banana
Anise	Collard ^a	Mustard greens ^a	Cactus leaves (nopales)	Avocado: ripe	Raspberry	Cactus pear, tuna	Mandarin	Breadfruit
Artichoke	Corn; sweet, baby	Parsley ^a	Calabaza	Barbados cherry	Strawberry	Calamondin	Olive	Canistel
Arugula ^a	Cut vegetables	Parsnip	Chayote ^a	Blackberry	Kiwifruit ^a	Carambola	Orange	Casaba melon
Asparagus ^a	Daikon ^a	Radicchio	Cowpea (southern pea)	Blueberry	Loganberry	Cranberry	Passion fruit	Cherimoya
Beans: fava, lima	Endive, chicory ^a	Radish	Cucumber ^a	Boysenberry	Longan	Custard apple	Pepino	Crenshaw melon
Beans sprouts	Escarol ^a	Rutabaga	Eggplant ^a	Caimito	Loquat	Durian	Pineapple	Honeydew melon
Beet	Fennel	Rhubarb	Kiwano (horned melon)	Cantaloupe	Lychee	Feijoa	Pummelo	Jaboticaba
			Squash: winter (hard rind) ^a					

Belgian endive ^a	Garlic	Salsify	Long bean	Sweet potato ^a	Cashew apple	Nectarine	Granadilla	Sugar apple	Jackfruit
Bok choy	Green onion ^a	Scorzonea	Malanga	Taro	Cherry	Peach	Grapefruit ^a	Tamarillo	Mamey
Broccoli ^a	Herbs (not basil) ^a	Shallot	Okra ^a	Tomato: ripe, mature green	Coconut	Pear: Asian, European	Guava	Tamarind	Mango
Broccoflower ^a	Horseradish	Snow pea ^a	Pepper: bell, chilli	Yam ^a	Currant	Persimmon ^a	Juan canary melon	Tangelo	Mangosteen
Brussels sprouts ^a	Jerusalem artichoke	Spinach ^a	Squash: summer (soft rind) ^a		Cut fruits	Plum	Kumquat	Tangerine	Papaya
Cabbage ^a	Kailan	Sweet pea ^a	Tomatillo		Date	Plum cot	Lemon ^a	Ugli fruit	Persian melon
Carrot	Kale	Swiss chard	Wingbean		Dewberry	Pomegranate		Watermelon	Plantain
Cauliflower ^a	Kohlrabi	Turnip							Rambutan
Celeriac	Leek ^a	Turnip greens ^a							Sapodilla
Celery ^a	Lettuce ^a	Water chestnut							Sapote
Chard ^a		Watercress ^a							Soursop

Note: Ethylene level should be kept below 1 ppm in storage area.

^a Sensitive to ethylene damage.

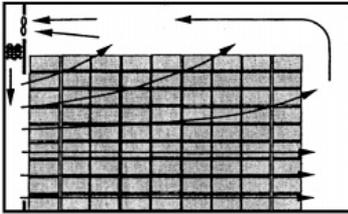
Maintaining storage temperatures within the prescribed range depends on several important design factors. The refrigeration system must be sized to handle the maximum expected heat load. Undersized systems allow air temperature to rise during peak heat-load conditions, while an oversized system is unnecessarily expensive. The system also should be designed so that air leaving the refrigeration coils is close to the desired temperature in the room. This prevents large temperature fluctuations as the refrigeration system cycles on and off. Large refrigeration coils installed with suction pressure controls allow a small temperature difference to be maintained between the air leaving them and the air in the room while still having adequate refrigeration capacity. A small temperature difference also increases relative humidity in the room and may reduce frost build-up on the coils. A large free space above the stored product allows air from the evaporators to mix with room air before coming in contact with stored product.

Temperature variation is minimized with adequate air circulation. Most stores are designed to provide an airflow of $0.3 \text{ m}^3 \cdot \text{min}^{-1}$ per tonne (100 cfm per ton) of product, based on the maximum amount of product that can be stored in the room. This is needed to cool product to storage temperature and also may be needed if the product has a high respiration rate. This high airflow rate can cause excessive weight loss from products, and fans are a significant source of heat, so the system should be designed to reduce air flow to 0.06 to $0.12 \text{ m}^3 \cdot \text{min}^{-1}$ of airflow per tonne (20 to 40 cfm per ton) after product has reached storage temperature. Motor speed-control systems, such as variable-frequency controllers for alternating current motors, are used to control fan speed at the lowest possible speed that will prevent unacceptably warm product in the storage. The warmest product tends to be near the top of the room and next to a warm wall or roof.

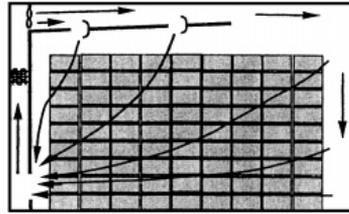
Low circulation rates require that the system be designed to move air uniformly past all of the stored product. Figure 3.29 shows some systems used to uniformly distribute air in large storage rooms. If air flows past the sides of bins or pallet loads, product must be stacked to form 10 to 15 cm wide air channels past the sides of each unit. Channels are formed parallel to the direction of air movement. There also should be space between product and walls to allow refrigerated air to absorb heat conducted from the outside. Curbs installed on the floor next to walls guarantee that product will be loaded with an air space between it and walls. If forklift openings are used for air distribution, bins may be tightly stacked and forklift openings must align along the entire length of the air path. The serpentine airflow system (sometimes called the *letter-box system*) is the only one that forces air to flow through product. This speeds initial cooling but may not be necessary for uniform product temperatures in long-term storage.

Air takes the path of least resistance, and partially filled rooms often have very uneven air distribution. Large rooms can be divided into sections with uninsulated walls parallel to the direction of air flow. This allows product in one bay to be removed with little effect on airflow in neighboring bays. Smaller rooms with packaged evaporator coils use an airflow pattern similar to the ceiling plenum design, except the plenum is not needed because high-capacity evaporator fans can discharge air at least 15 m. The wall plenum is formed by stacking product 20 to 25 cm away from the wall under the evaporator. Rooms cooled with roof-mounted packaged evaporative coolers sometimes use ceiling-mounted paddle fans to distribute air downward past bins of product.

Air flow through spaces between bins or pallet loads

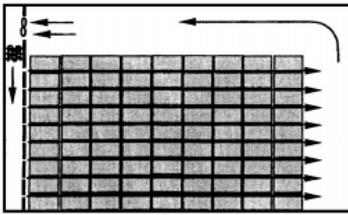


vertical slots in supply plenum

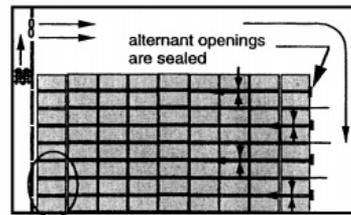


ceiling plenum with turning vanes

Air flow through forklift openings in bins



horizontal slots in supply plenum



serpentine air flow

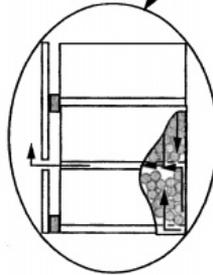


Figure 3.29. Air-flow distribution systems used in cold storages. Figures are side elevations with evaporator coil and fan on top left.

In some long-term controlled-atmosphere storages, airflow is minimized by cycling evaporator fans off for as much as 85% to 90% of the time. In the winter in temperate climates, most refrigeration demand comes from heat released by evaporator fan motors. Reducing fan operation time reduces heat input, which in turn reduces refrigeration operation. During tests in the northwestern United States, fan cycling reduced fan operation use by 60% to 65% and electricity use by 50% to 55% compared with continuous fan operation [3]. It also may increase humidity in the storage and reduce product moisture loss.

Thermostat sensors are usually placed 1.5 m above the floor (for ease of checking) in representative locations in the room. They should not be placed near sources of heat such as doors or walls with an exterior surface. Nor should they be placed in a cold area such as near the air discharge of the refrigeration unit. A calibrated thermometer should be used to periodically check the thermostat, because errors of only a few degrees can significantly affect product quality.

Humidity

For most perishable commodities, the relative humidity in a storage facility should be kept at 90% to 100% (Appendix, Table 3.A3). Humidities below this range result in unacceptable moisture loss. However, humidities close to 100% may cause excessive growth of microorganisms and surface cracking on some products, although it is unusual for a storage facility to have relative humidities that are too high.

Partially dried products such as garlic, ginger, and dry onion are held at 65% to 75% humidity. Dried fruits and nuts should be held at 55% to 65% humidity. Corrugated fiberboard or cardboard containers are weakened by prolonged exposure to high humidity. Typical corrugated fiberboard exposed to 95% humidity has half as much strength as the same material exposed to 50% humidity. Storage-room humidity for perishables can be lowered below recommended levels if the product is packaged in plastic bags or box liners to maintain a high relative humidity around the product and prevent moisture loss.

Refrigeration equipment must be specially designed to maintain high relative humidity. In systems not designed for horticultural commodities, the evaporator coils (which produce cold air) operate with a refrigerant temperature at least 11°C (20°F) lower than the temperature of the air returning to the coil. This causes an excessive amount of moisture to condense on the coils and results in a low relative humidity in the storage room. Coils with a large surface area achieve the same refrigeration capacity as smaller coils but can operate at a higher temperature, thus reducing the moisture removed from the air. As a guide, the coils should be large enough so that the refrigerant is only 2.2 to 4.4°C colder than the air temperature returning to the coil [4].

Mechanical humidifiers or fog spray nozzles are sometimes used to add moisture to the storage room and reduce the drying effect of the evaporator coils. They are particularly valuable if moisture must be added to wood or paper packaging to prevent it from absorbing moisture from the product. However, much of the moisture added by a humidifier is condensed on the evaporator, resulting in the need for more frequent defrosting. Humidifiers also are needed in conditions under which the product is stored at a temperature warmer than the outside environment (cold winter locations) and heat is added to prevent chilling injury or freezing.

Some refrigeration systems use a wet-coil heat exchanger to maintain humidity. In this system, water is cooled to 0°C, or a higher temperature if higher room temperatures are desired. The water is sprayed down through a coil, and the storage area air is cooled and humidified to nearly 100% as it moves upward through the coil. However, as the air moves through the storage area it picks up heat, and the rise in temperature reduces relative humidity. This system usually is limited to air temperatures above 0.2°C, and it does not work well for commodities that are held close to or below 0°C, without the

use of compounds that depress freezing temperature (such as caustic soda or ethylene glycol) in the water.

3.4.3 Refrigeration

Mechanical Refrigeration

Most storage facilities use mechanical refrigeration to control storage temperature. This system utilizes the fact that a liquid absorbs heat as it changes to a gas. The simplest method for using this effect is to allow a controlled release of liquid nitrogen or liquid carbon dioxide in the storage area. As the refrigerant boils, it causes a cooling effect in the storage area. However, this method requires a constant outside supply of refrigerant and is used only to a limited extent with highway vans and rail cars. The more common mechanical refrigeration systems use a refrigerant such as ammonia or a variety of halocarbon fluids (sometimes referred to by the trade name Freon) whose vapor can be recaptured easily by a compressor and heat exchanger.

Figure 3.30 shows the components of a typical vapor-recompression (or mechanical) refrigeration system. The refrigerant fluid passes through the expansion valve, where the pressure drops and the liquid evaporates at temperatures low enough to be effective in removing heat from the storage area. Heat from the material to be cooled is transferred to the room air, which is then forced past the evaporator (cooling coil located in the room). This is usually a finned tube heat exchanger, which transfers the heat from the air to the refrigerant, causing it to evaporate. After fully changing to a gas, it is repressurized by the compressor and then passes through a condenser, where it is cooled to a liquid. The condenser is located outside the storage area and releases heat. Liquid is stored in the receiver and is metered out as needed for cooling.

Refrigerant Flow and Pressure Control

Small mechanical refrigeration systems are controlled primarily by the expansion valve, which regulates the pressure of the refrigerant in the evaporator. Low pressures cause the liquid refrigerant to evaporate at low temperatures. The valve also controls the flow of refrigerant, which affects the amount of refrigeration capacity available. Capillary tubes and thermostatic expansion valves are the most common types of expansion valves.

The capillary tube is used with very small refrigeration equipment (less than 0.7 kW [1 hp]). It is a tube 0.6 to 6 m long with a very small inside diameter of 0.6 to 2.3 mm. The resistance of the liquid flowing through the tube creates the needed pressure drop between the low-pressure and high-pressure sides of the system and regulates the flow of refrigerant. A capillary is inexpensive and has no moving parts to maintain, but it cannot be adjusted, is subject to clogging, and requires a relatively constant weight of refrigerant in the system.

The thermostatic expansion valve regulates the flow of refrigerant to maintain a constant temperature difference between the evaporator inlet or evaporating temperature and the coil outlet (it maintains a constant superheat of the refrigerant above its evaporation temperature). It allows the evaporator pressure to vary, so that when high refrigeration

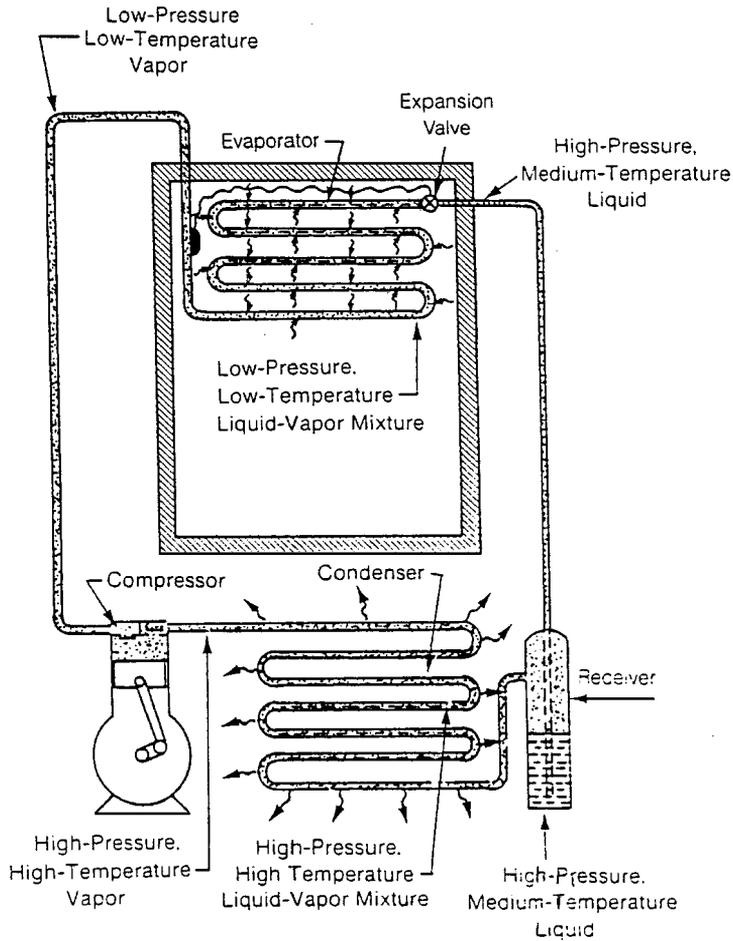


Figure 3.30. Schematic of a typical vapor recompression or mechanical refrigeration system.

capacity is required, the temperature of the evaporator coil increases. Evaporator coils with this control system are commonly called *direct-expansion systems*. This type of expansion valve is not well suited to obtaining high relative humidity needed in long-term storage and is rarely used with ammonia refrigerant.

Large refrigeration systems may use evaporator coils that are designed always to have liquid refrigerant in them, called a *flooded coil* or a *forced-liquid recirculation system*. Refrigerant flow is controlled primarily with a float control that ensures a constant level of refrigerant in the coil. The float control may operate in parallel with a thermostatic expansion valve. These designs have a greater heat-transfer efficiency than a direct-expansion coil of equal size. Other controls such as suction-pressure regulators may be used in conjunction with float controls. These are especially useful in maintaining the

Table 3.28. Effect of increasing design and operating parameters on evaporator performance

Parameter Increased	Outlet Air		Refrigeration Capacity	Typical range
	Temperature	Humidity		
Face area	Lower	Lower	Higher	Depends on refrigeration capacity
Number of tube rows deep	Lower	Lower	Higher	4–8
Fin spacing	Lower	Lower	Higher	150–300 fins/m (4–8 fins/in)
Face velocity	Higher	Higher	Higher	2–4 m · s ⁻¹ (400–800 feet per minute)
Refrigerant temperature	Higher	Higher	Lower	3–8°C (5–15°F) below entering air

Source: [4].

highest possible evaporator-coil temperature to maintain high humidity in the storage room. Flooded evaporators tend to reduce energy costs but are more expensive to install compared with direct-expansion units.

Evaporators

Cold storages usually are equipped with finned tube evaporators. Air from the storage is forced past the tubes by fans, which are a part of a complete evaporator unit. Coil-unit selection is based on the area of the coil perpendicular to the direction of air flow (called *face area*), number of rows of tubes in the direction of air flow, fin spacing, airflow rate through the coil, and refrigerant temperature. Table 3.28 summarizes the effect of these factors on refrigeration system performance. Manufacturers provide data on the effects of these factors on performance of their equipment.

Evaporators operating below 0°C build up frost that must be removed to maintain good heat-transfer efficiency. Defrosting may be done by periodically flooding the coils with water, by electric heaters, by directing hot refrigerant gas to the evaporators, or by continuously defrosting with a brine or glycol solution. In storages with air temperatures above 2°C frost can be melted by shutting off the refrigerant supply and letting the room air heat the evaporator.

Compressors

The most common types of refrigeration compressors are reciprocating (piston) and screw (Fig. 3.31). Reciprocating compressors come in a wide range of sizes and can be set up to operate efficiently at varying refrigerant flow rates. Rates are varied by shutting off pairs of cylinders in a unit that may have 6 to 12 cylinders. The main disadvantage of reciprocating compressors is their fairly high maintenance costs, although maintenance often can be done in onsite. Screw compressors have low maintenance costs but are not available in sizes smaller than about 23 kW (30 hp) and do not operate efficiently at partial loading. Some facilities use screw compressors for base-load refrigerant needs and reciprocating compressors for the portion of the load that varies significantly during the day.

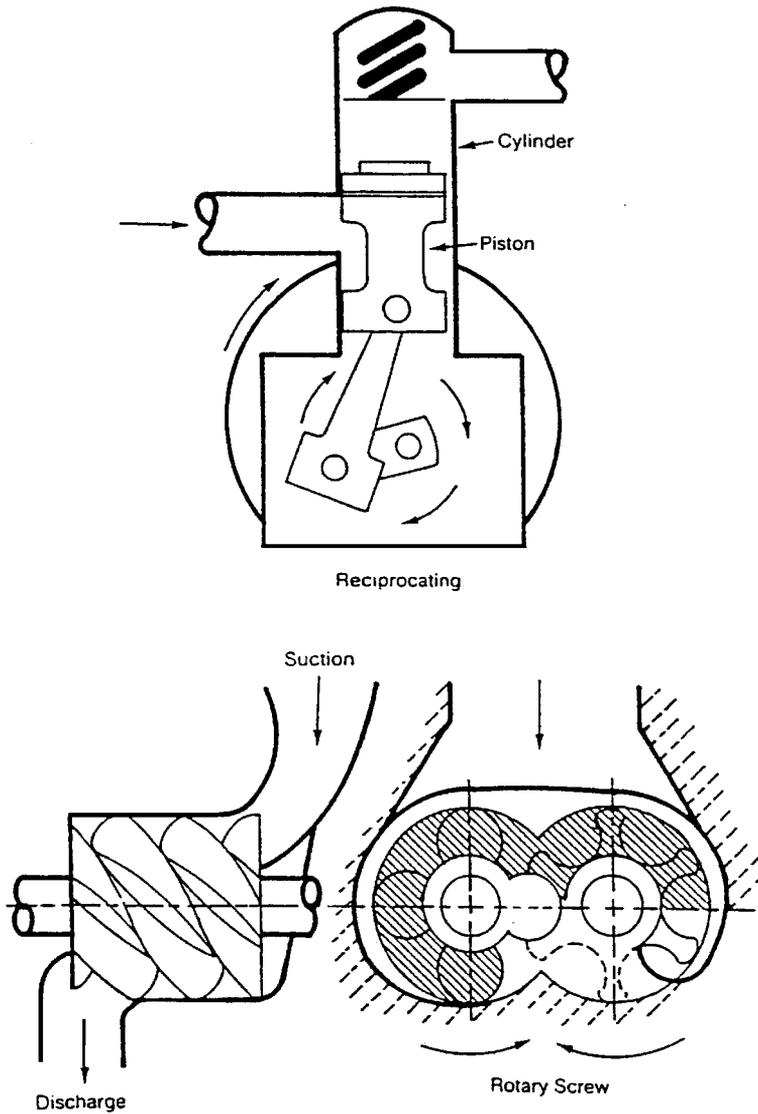


Figure 3.31. Common types of refrigeration compressors.

Maintaining the highest possible suction pressure reduces compressor energy use. This can be achieved by using large evaporator coils and a control system that increases suction pressure as demand on the refrigeration system is reduced. A compressor system that operates efficiently over the required range of refrigerant flows is recommended. Screw compressors operate efficiently only at flow rates near their maximum capacities. Several can be used in parallel, shutting down those that are not needed, or reciprocating

Table 3.29. Comparison of Refrigerants

	Ozone- Depletion Potential	Cost	Latent Heat at 15°C (kJ · kg ⁻¹)	Flow Leaving Evaporator (L · s ⁻¹ · kW ⁻¹)	Coefficient of Performance	Flammability
R-12*	1.0	—	—	—	—	—
R-22	0.55	Moderate	216	0.48	4.66	No
R-134a	0	High	208	0.82	4.60	No
R-507	0	Not available	175	0.45	4.31	Not available
R-717 (ammonia)	Not- available	Very low	1313	0.46	4.77	Moderate

* The properties are not listed because the refrigerant is no longer available.

Source: [5].

compressors can be used for peak loads, because they operate efficiently over a large range of refrigerant flows.

Condensers

Condensers are categorized as air-cooled, water-cooled, or evaporative. Air-cooled condensers are inexpensive and have low maintenance cost but often cause higher energy use compared with the other choices. Small systems usually use an air-cooled unit. Many home refrigerators, for instance, have a coiled tube in the back that allows a natural draft of air to flow past. Systems with a few kilowatts of motor power use a fan to provide airflow past the condenser. Large condensers are more likely to be water-cooled. Water is a better heat conductor than air, allowing water-cooled condensers to be smaller than forced-air units of equal capacity. However, water-cooled units may require large quantities of water, which can be expensive to obtain and dispose of. Evaporative condensers reduce water consumption by recycling the heated condenser water; they require close attention to water quality to maintain efficiency and to prevent damage to the heat exchanger.

Energy use is minimized by selecting a condenser that cools the refrigerant fluid to as low a temperature as possible. For example, a facility maintaining 0°C and a condensing temperature of 52°C requires 50% more power than one that operates at a condensing temperature of 35°C. In warm areas, well water-cooled or evaporatively cooled condensers should be selected over air-cooled units.

Refrigerants

Ammonia and a number of halocarbon fluids are commonly used refrigerants. Some of the properties of the most common refrigerants are listed in Table 3.29. Refrigerant 12 (R-12) has been classified as an atmospheric ozone-depleting chemical and soon will be unavailable.

The choice of which refrigerant to use in a vapor recompression system is based on the following factors:

Cost

Halocarbon refrigerants are more expensive than ammonia, and R-134a is significantly more costly than ammonia.

Efficiency

Under standard operating conditions ammonia is slightly more efficient than the halocarbon refrigerants as measured by coefficient of performance. Its latent heat is much higher than the halocarbons, meaning that less pumping energy is required.

Flammability

Ammonia is moderately flammable, and large systems must be designed to allow good fire control. Refrigerants 22 and 134a are basically not flammable.

Compatibility

Ammonia cannot be used with metals that contain copper; halocarbon refrigerants cannot be used with alloys containing more than 2% magnesium and may damage some elastomeric materials.

Toxicity

Ammonia at very low concentrations can injure perishable commodities. It is toxic to humans, and some governments require ammonia systems to have equipment to confine accidental releases and a plan for protecting personnel and neighbors from an accidental release.

Refrigerant Piping and Vessels

Piping is used to transfer refrigeration liquid or vapor from one component to the another. Piping size is based on the volume handled and the acceptable fluid velocity in the pipe. For example, vapor piping is larger than piping for liquid refrigerant. A large-diameter pipe reduces fluid velocity and therefore reduces pressure drop and increases plant efficiency, but it is more expensive than a smaller pipe. Pipe selection also must allow for the need to transport oil and to permit or prevent liquid flow in a pipe that has both liquid and vapor. Vessels are needed in large operations to store liquid refrigerant and separate mixtures of liquid refrigerant and vapor.

Control Systems

A large refrigeration system requires a good control system and equipment for displaying the system's operating condition. At a minimum, panel lights should be installed to indicate the operating status of fans and compressors, and the fluid levels in surge and receiver tanks. Controls should be set up to allow manual operation of motors.

Microcomputers and programmable controllers allow even more precise control of large refrigeration systems. They are especially valuable in reducing electricity use during peak-rate periods. Defrost cycles can be programmed to take place at night, and unnecessary fans and compressor motors can be turned off during peak-rate periods.

3.4.4 Absorption Refrigeration

Absorption refrigeration is used in a few cold-storage operations. It differs from mechanical refrigeration in that the vapor is recovered through use primarily of heat rather than of mechanical power. It is less energy-efficient than mechanical refrigeration and usually is used only where an inexpensive source of heat is available. Processing facilities with excess low-pressure steam are well suited to absorption refrigeration.

3.4.5 Secondary Refrigerants

Some storages are cooled with a secondary coolant. A brine solution, either sodium chloride, calcium chloride, or glycols (commonly propylene glycol or ethylene glycol), is cooled by a mechanical refrigeration system and pumped to heat exchangers in the cold storage. These systems are a little less energy-efficient than conventional systems, and brine solutions are corrosive, but they dramatically reduce the quantity of first-stage refrigerant needed and confine it to the compressor room. This is a great asset in dealing with the flammability and safety issues of ammonia. Secondary-refrigerant piping does not need to withstand the pressure of primary refrigerants, and this may allow plastic piping to be used. Heat-exchanger temperature can be controlled precisely with a mixing valve. Brines and glycol solutions are corrosive; they must be used with corrosion inhibitors and should never be in contact with zinc. Sodium chloride and propylene glycol are food-grade materials.

3.4.6 Refrigeration Load Calculations

Information on peak heat load is needed to size refrigeration components. These calculations are based on extreme heat-load assumptions so that equipment will dependably maintain temperature. Designers add about 10% to 20% extra refrigeration capacity above their calculations to ensure that the equipment will perform well even under unforeseen circumstances. In multiroom facilities, a calculation is done for each room to select an evaporator and piping. Compressor and condenser capacities are based on peak load contribution from all rooms, which is usually less than the sum of the peak loads for each individual room, because the rooms are not all exposed to peak loads at the same time.

Heat-load calculations also can be used to estimate total energy use of the facility, perhaps for financial-planning purposes. These calculations are based on average conditions during each week or month of operation.

The heat load to which a refrigeration system is exposed is based on adding all the heat inputs to a storage area. These include heat conducted through walls, floor, and ceiling; field and respiration heat from the product; sensible and latent heat from air infiltration; defrost heat; and heat from personnel and equipment such as lights, fans, and forklifts. A typical range of refrigeration load for a produce storage is 9.9 to 13.7 kW per 1000 m³ (0.08 to 0.11 ton per ft³) and for a shipping dock is 13.7 to 25 kW per 1000 m³ (0.11 to 0.20 ton per ft³) [5]. Procedures for detailed heat load calculations are given in refs. [2] and [5].

Refrigeration equipment for storage facilities usually is not designed to remove much field heat from the product because a large capacity is required; a separate cooling facility usually is used for this purpose [6].

3.4.7 Alternative Refrigeration Sources

In many developing countries, where mechanical refrigeration is prohibitively expensive to install, maintain, and operate, a number of other techniques can be used to produce refrigeration. In some cases these can provide nearly the recommended storage

conditions. In others, they are a compromise between proper storage conditions and costs for equipment, capital, and operations.

Evaporative Cooling

Evaporation of water requires heat. Evaporative-cooling systems extract this heat from the product. Evaporative-cooling techniques are very energy-efficient and economical [7]. A well-designed evaporative cooler produces air with a relative humidity greater than 90%. Its main limitation is that it cools air only to the wet-bulb temperature of the outside air. During the harvest season in the United States, wet-bulb temperatures vary from 10 to 25°C depending on location, time of day, and weather conditions. This temperature range is acceptable for some chilling-sensitive commodities.

The water for cooling in the systems mentioned previously comes from domestic sources. It is also practical to cool by evaporating water from the commodity. Snap beans have been cooled in transit by erecting an air scoop above the cab of the truck that forces outside air through a bulk load of beans [8]. This system prevents heat build-up and keeps the beans at or below the outside air temperature. Using this system for any great length of time may result in excessive water loss.

Night Cooling

In some parts of the world, significant differences between night and day temperatures allow nighttime ventilation to be a means of refrigeration. In dry Mediterranean or desert climates the difference between daily maximum and minimum temperatures can be as great as 22°C during the summer. Night cooling is commonly used for unrefrigerated storage of potatoes, onions, sweet potatoes, hard-rind squashes, and pumpkins. As a rule, night ventilation effectively maintains a given product temperature if the outside air temperature is below the desired product temperature for 5 to 7 hours per day.

Low nighttime temperatures can be used to reduce field heat simply by harvesting produce during early-morning hours. Some growers in California use artificial lighting to allow night harvest.

It is theoretically possible to produce air temperatures below nighttime minimums by radiating heat to a clear sky. A clear night sky is very cold, and a good radiating surface such as a black metal roof can cool air below ambient temperature. Simulations have indicated that this method could cool air about 4°C below night air temperatures. This concept has not yet been used widely.

Well Water

In some areas, well water can be an effective source of refrigeration. The temperature of the ground more than about 2 m below the surface is equal to the average annual air temperature. Well water is often very near this temperature.

Naturally Formed Ice

Before the development of mechanical refrigeration, refrigeration was provided by natural ice harvested from shallow ponds during the winter. The ice was stored in straw and hauled to cities as needed during spring and summer. Energy costs today make it unfeasible to transport ice any significant distances. However, cooling facilities in

appropriate climates can store ice nearby for summer use. In some cases, it may be feasible to transport perishable commodities to the ice for storage. This would be especially practical where the ice is located between the sites of production and consumption.

High-Altitude Cooling

High altitude also can be a source of cold. As a rule of thumb, air temperatures decrease by 10°C with every kilometer (5°F per 1000 ft) increase in altitude. It is not possible to bring this air down to ground level because it naturally heats by compression as it drops in altitude. However, in some cases it may be possible to store commodities at high altitudes in mountainous areas. For example, in California most perishable commodities are grown in the valley floors near sea level. However, much of the production is shipped east across the Sierra Nevada over passes about 1800 m high. Air temperature has the potential of being 18°C cooler, and it may reduce energy costs to store perishables there rather than on the valley floor.

Underground Storage

Caves, cellars, abandoned mines, and other underground spaces have been used for centuries for storage of fruits and vegetables. As mentioned previously, underground temperature is near the average annual air temperature. Underground spaces work well for storing already cooled produce but not for removing field heat. The soil has a poor ability to transfer heat. Once the refrigeration effect is depleted from an area, it does not regenerate rapidly. This can be overcome by installing a network of buried pipes around the storage. Cooled air is pumped from the pipes to the storage area, allowing the harvest of cooling capacity from a greater soil volume.

3.4.8 The Storage Building

Size

The storage must be sized to handle peak amounts of product. The floor area can be calculated knowing the volume of the produce and dividing by the maximum product storage height and adding area for aisles, room for forklift maneuvering, and staging areas. Maximum storage height can be increased by use of shelves or racks and forklifts with suitable masts. Multistory structures generally are not used because of the difficulty and expense of moving the product between levels.

The building ideally should have a floor perimeter in the shape of a square. A rectangular configuration has more wall area per unit of floor area, resulting in higher construction cost and higher heat loss compared with a square configuration. Entrances, exits, and storage areas should be arranged so that the product generally moves in one direction through the facility, especially if the storage facility is used in conjunction with a cooler to remove field heat.

Site Selection

Good utility service must be available for the facility. Extending roads and energy utilities to a facility can be very expensive. Three-phase electrical power is needed to

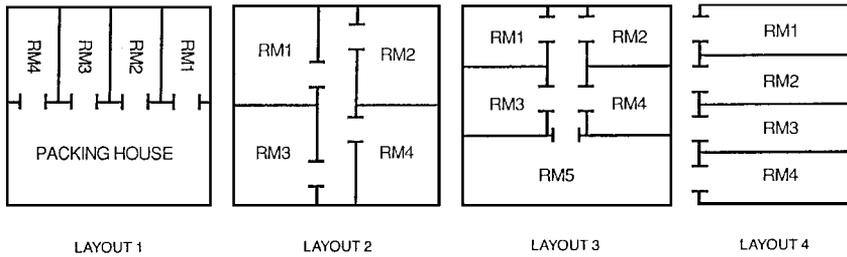


Figure 3.32. Typical layouts of cool-store facilities.

operate refrigeration-equipment motors. In some areas a back-up power supply may be advisable. There should be enough water to supply the evaporative condensers, personnel needs, and the needs of a packing house, if it is a part of the project. The availability of fire-protection services, gas supply, and sewer utilities also should be considered.

The area should have good drainage and room for future expansion. There should be enough space around the facility for smooth movement of large highway trucks.

Building Layout

Room layouts with an interior corridor offer better operating conditions for cold storages and better control of controlled atmosphere storages than designs that allow room access only through exterior doors. The interior corridor, seen in layouts 1 through 3 in Fig. 3.32, allows easy access to piping and controls. Doors and equipment are shielded from the elements, and product observation is easier. Layout 1 is common in small operations in which storage and packing are done in one building. Layout 2 allows better product flow compared with layout 3, but layout 3 has less area devoted to corridor. Layout 4 is the least expensive of the designs, because none of the cold-storage building is used as a permanent corridor.

Refrigerated facilities can be constructed from a wide variety of materials. The floor and foundation are usually concrete. A vapor barrier is installed to prevent moisture movement through the floor, and rigid insulation is sometimes placed above the barrier and below the concrete. Walls can be made of concrete block, tilt-up concrete, insulated metal panels, or wood-frame construction. In large facilities wood frame and concrete block are losing favor to metal and tilt-up concrete construction in the United States.

Walls are insulated with fiberglass batts, rigid urethane foam boards, or sprayed-on foam. Batt and board insulation must be protected with a vapor barrier on the warm side. Properly applied sprayed-on foam can be moisture-proof. Exposed foam insulation must be coated with a fire retardant. Some storages combine insulation types: For example, the interior can be sprayed with foam to form a vapor barrier, then covered with batt or board insulation for appearance and fire protection. If modified atmosphere techniques are used in the storage facility, the vapor barrier also may serve as a gas barrier, and special precautions must be taken to ensure a gastight seal.

Total wall insulation level, measured in heat-resistance units, is often in the range of 3.5 to 7.0 $\text{m}^2 \cdot ^\circ\text{K} \cdot \text{W}^{-1}$ (equal to an R-value of 20 to 40 $\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{BTU}$). Ceilings can be

insulated with rigid board or foam materials, or built separately from the roof and insulated with loose fill or batts. Ceiling heat resistance of at least $10.6 \text{ m}^2 \cdot ^\circ\text{K} \cdot \text{W}^{-1}$ (R60) is common in new construction. In general, it is advisable to build with more insulation than utility costs presently may warrant, because energy costs are difficult to predict and it is much cheaper to install insulation during construction than after construction is completed.

Sun shining on walls and roof can dramatically increase the effective outside temperature of a wall, increasing heat flow into a storage facility. A dark, flat roof can be 42°C warmer than the outside air temperature. Painting a south-facing wall a light color can reduce the effective wall temperature by 11°C compared with a dark wall. Walls and roof of a cold-storage facility should be painted a light color or shaded from the direct sun.

Warm outside air leaking into the cold storage room increases energy use. Plastic flap doors reduce infiltration during loading and unloading. Sealant should be placed around openings for pipes and electrical conduits. Loading docks for out-bound product should be fitted with flexible bumpers that provide an airtight seal between the dock and the truck.

High-efficiency lighting sources, such as metal halide lamps, reduce heat input to the cold storage, and turning off lights when not needed reduces unnecessary heat load.

3.4.9 Other Options for Small-Scale Cold Rooms

Cold rooms for small-scale operations can be purchased from commercial suppliers, self-built, or made from used refrigerated equipment such as rail cars, marine containers, or highway vans [9]. The choice of the best system is based on cost and availability of equipment in the area and the amount of time available to invest in cold-room installation.

Rail Cars

Refrigerated rail cars are sometimes available for farm use. They are very sturdy and well insulated. Refrigeration is driven by an electric motor powered by a diesel generator. The generator set can be salvaged and the refrigeration connected to the farmer's electric utility. Railcars in the United States have a 2.84 m-high ceiling, which limits the height to which produce can be stacked. The most significant problem and greatest cost of using railcars is getting them from the railroad to the farm site.

Highway Vans

The one unique advantage of highway vans is that they are portable if the wheels are left on. The refrigeration system is powered directly with a diesel engine. This can be a benefit if utility electricity is not available at the site. In some areas, it may be less expensive to operate the refrigeration unit if it is converted to operate with an electric motor, but a considerable conversion cost must be added to the project. Highway vans are built as light as possible to maximize the load they can carry; this often means that used vans are in fairly poor condition. Their insulation, which is limited to begin with, may have deteriorated, and they may have poorly sealed doors that permit excess air leakage. Also, old vans often have fairly small fans that may not provide adequate air circulation.

Marine Containers

These are available in lengths of 6.1, 7.3, and 12.2 m (20, 24, and 40 ft). Their built-in refrigeration units are powered with 220- or 440-V, three-phase electricity, and they can be plugged directly into utility power. They are usually well built and have deep T-beam floors and sufficient fan capacity to provide good air circulation; in fact, air circulation is good enough to allow adequate room cooling.

A disadvantage of all transport vehicles is that their refrigeration systems usually are not designed to produce high relative humidity. Drying of the product due to low humidity results in weight loss and poor quality. This is particularly a problem if the cold room is to be used for long-term storage. Drying can be reduced by keeping the floor and walls of the cold room wet, but this causes increased corrosion, reduced equipment life, and increased need for defrosting.

Refrigerated transport vehicles rarely have enough refrigeration capacity to cool produce rapidly. If rapid cooling is needed, extra capacity must be added. Moreover, transportation vehicles are too narrow for the frequent product movement needed in a precooling facility. A separate self-constructed room is much more convenient for precooling operations.

Self-Constructed Cold Rooms

For many producers, a self-built cold room is the least expensive option. It usually is built with a concrete or wood-frame floor. Walls and roof are of wood-frame construction and insulated with fiberglass batts. Care must be taken to install a tight vapor barrier on the warm side of the insulation. Refrigeration is provided by a small mechanical refrigeration system. If the room is kept above 10°C, it may be possible to use a room air conditioner. These cost about half as much as a packaged refrigeration system.

3.4.10 Controlled-Atmosphere Storage

Controlled-atmosphere (CA) storage utilizes oxygen and carbon dioxide concentrations of about 1% to 5% for each gas. Normal room air has an oxygen concentration of about 21% and a carbon dioxide level near 0.03%. Low oxygen and high carbon dioxide levels slow ripening processes, stop the development of some storage disorders (such as scald in apples), and slow the growth of decay organisms. All of these effects increase storage life of fresh produce compared with refrigerated air storage. More details about the potential benefits and hazards of CA storage are presented in Section 3.2. CA storage has all of the design requirements of conventional refrigerated storage plus gastight rooms, equipment to obtain the desired gas concentrations, and equipment to measure and control atmospheric composition [10].

Simple CA System

The simplest system for obtaining gastight storage uses a plastic tent inside a conventional refrigerated storage room. The tent is made of 0.10- to 0.15-mm polyethylene sheeting supported by a wood framework. The sheeting is sealed to the concrete floor by pressing the plastic into a narrow trough and forcing tubing into the trough to keep the plastic in place. A better gas barrier at the floor can be obtained by laying a sheet of plastic on the floor and protecting it with wood panels. A seal is obtained by joining

the tent to the floor sheet. A fan inside the tent provides air circulation. The oxygen level is reduced initially by allowing fruit respiration to consume oxygen, or by using CA generators. Oxygen is kept above the minimum by allowing a controlled amount of outside air to enter the tent. The CO₂ level is maintained by placing bags of fresh hydrated lime in the tent to absorb excess CO₂.

Permanent CA Facilities

Permanent facilities require that the storage plant be designed specifically for controlled atmosphere storage. Usually a CA facility costs about 5% more to build than a conventional refrigerated storage facility. The extra cost is in building the storage rooms to be airtight and, in some cases, designing smaller individual rooms than are needed in common refrigerated storage.

Individual rooms should be sized to allow them to be filled in a short time. Many apple CA rooms are built to hold a week's fruit harvest. If an operator wishes to use rapid CA, the room should be small enough to be filled in 3 days. Many facilities have several room sizes to allow for variations in incoming fruit volume, fruit varieties, and marketing strategy.

Modern storages are single-story designs, with individual rooms often tall enough to allow fruit to be stacked 10 bins high, including enough height between the bins and the ceiling for air from the evaporator coils to mix with the room air and to travel easily to the far end of the room.

Gas-Tight Construction

Floors and doors are designed to maintain gastightness. Three main types of interior wall and ceiling construction are used in recently built CA storages.

Urethane System

Urethane foam serves as a gas seal, insulation, and vapor barrier. But it is expensive, primarily because the urethane must be covered with a fire barrier. Foamed-in-place urethane can be applied directly to any type of masonry, wood, or primed metal. It should not be applied over rigid board insulation as the foam can distort the board, and board materials that are not tightly attached cause the gas seal to fail over time. Figure 3.33 shows a cross-section of a typical CA storage sealing system with urethane-foam insulation.

Plywood Cover Over Fiberglass Insulation

This is a common method of insulating and sealing CA storages. It is usually the least expensive of the three gas-barrier systems. The plywood sheets are sealed with a butyl rubber compound applied between the sheet and the wood framing. Sheets are separated with a 3-mm gap to allow for expansion. The gap is filled with butyl rubber and the joint covered with fabric and an elastomeric sealer. If regular plywood is used, the whole board must be covered with the sealer. High-density plywood does not need to be treated for gastightness.

A vapor barrier usually is installed on the outside (warm side) of the insulation. However, an outside vapor barrier is not recommended with the plywood system, because there is already a gastight seal on the inside of the insulation. A vapor barrier on the

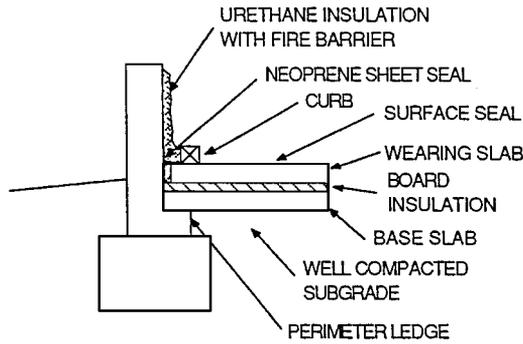


Figure 3.33. Gastight seal using urethane foam insulation.

outside will trap any moisture that might get into the insulation, ruining its insulating value.

Insulated Panels

These are usually a sandwich design. Eight to fifteen centimeters of rigid foam insulation is covered on both sides with painted metal or fiber reinforced plastic sheets. Panels are 1.2 to 2 m wide and usually extend from floor to ceiling. The panels are installed inside a building shell and are held together with mechanical fasteners. Joints are sealed with polyvinylacetate copolymer or latex emulsion sealers. Large gaps are backed with a nonwoven fabric.

Floors

Floors can be made gastight with two main systems. An insulated floor is usually a sandwich design, with board insulation placed between two layers of concrete. With this design, a gas seal of two layers of hot-mopped asphalt roofing felt is applied to the subfloor. A single-slab floor is used if only perimeter insulation is used. In this case the floor is sealed by applying special materials to the top surface. Chlorinated rubber compounds are sometimes used.

In all designs, the wall-to-floor seal is the area that is most likely to fail. It is important to eliminate floor movement with respect to the wall by carefully backfilling and thoroughly compacting the subgrade. The floor can be tied to the walls with steel reinforcing bar or set on a 10-cm ledge built into the foundation wall.

Doors

Many different door designs can be used in CA facilities. In all of them the door is constructed of a solid frame that can be clamped tightly against a gasketed door frame without warping. The frame can be covered with well-sealed plywood or metal. Some of the more expensive doors have aluminum sheets welded to an aluminum frame. The bottom of the door usually is sealed with caulking compound after the door is closed. Most doors are 2.4 to 3 m (8 to 10 ft) wide and tall enough to allow a lift truck with two bins to pass through.

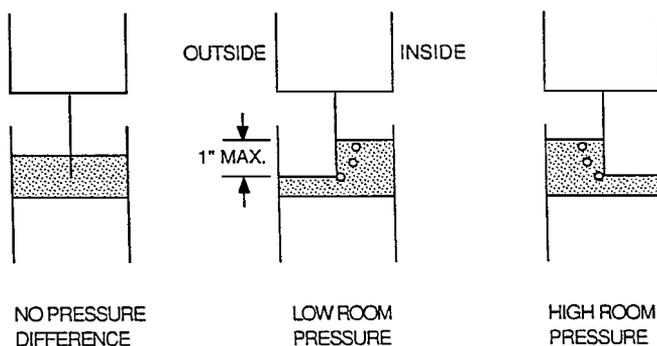


Figure 3.34. Schematic of water-trap pressure-relief system.

Each room also should have a 60 by 75 cm access door that allows for entry for checking fruit and making repairs without opening the main door. Many storages also have a fixed, clear acrylic window near the top of a wall to observe fruit without entering the room. It usually has a concave shape, allowing all areas of the room to be seen.

Pressure Relief

A pressure difference between the cold room and the outside can develop because of changes in weather or room temperature. This difference can damage gas seals or even the building structure if it is not relieved. A water trap as pictured in Fig. 3.34 is usually used to allow pressures to equalize. The trap is often filled with ethylene glycol to avoid problems with water evaporation. A spring-loaded or weight-loaded check valve can be used, but these are much more expensive than a simple water trap. Vent area should be 10 cm^2 per 40 m^3 of room volume (1 in^2 per 1000 ft^3).

Small changes in pressure can be relieved by using breather bags. These have the advantage of capturing the gas mixture in the room and allowing it to reenter the room at a later time. Bags should have 0.35 to 0.4 m^3 of capacity per 100 m^3 of room volume ($3.5\text{--}4 \text{ ft}^3/1000 \text{ ft}^3$), although some are designed with several times this capacity. If a CA room is so tightly sealed that air must be regularly bled into the room to maintain O_2 level, breather bags are not necessary.

Pressure Test

The overall gastightness of a CA room is tested by pressurizing it and measuring the rate of pressure drop. After all doors and openings are sealed, a small fan is used to increase the static pressure in the room to 2.5 cm of water column. The fan then is turned off and sealed, and the tester determines how long it takes for the pressure to drop by half. If this takes 20 minutes or longer, it is considered tight enough for a CA system that uses hydrated lime to maintain CO_2 levels. At least 30 minutes are required for rooms that use carbon or water scrubbers to control CO_2 . Some authorities believe that rooms should be even more gastight than these standards and require 45 minutes to 2 hours for the pressure to drop by half. Because gas seals deteriorate, new rooms should be much tighter than prevailing standards.

If the room does not meet the desired standard it is necessary to check for leaks. They are most common around doors, at the wall and floor junctions, near poorly sealed penetrations, and at unsealed electrical boxes. Testing for leaks can be done by putting the room under a slight vacuum and listening for air leaking, or by spraying suspect areas with soapy water and watching for bubbles. Smoke sticks or bee smokers can be used to detect streams of outside air entering the room.

3.4.11 Equipment for Atmospheric Modification

The least expensive but slowest method of changing the storage-room atmosphere is to let the product do it through natural respiration. Fruit and vegetables use oxygen and release carbon dioxide. The product in a sealed room eventually lowers the oxygen to the level needed for CA storage; if oxygen drops too low, outside air can be added to restore it to the desired level. However, respiration usually causes carbon dioxide levels to rise well above required levels. Bags of hydrated lime are used to absorb excess CO₂. Lime requirements are 1 to 3 kg per 100 kg of product, depending on the product being stored, storage time, surface area, and quality of the lime. Bags can be placed either in single layers in the CA room or in an adjacent lime room that is connected to the CA room with a fan and ductwork. Rooms should be sized to hold about 15 kg of lime per ton of product. Lime is very effective in producing the low levels of CO₂ that are increasingly used in apple storage.

Carbon dioxide levels also can be controlled with activated-carbon adsorption systems, or molecular sieves. Molecular sieves tend to use more energy than activated-carbon systems.

Relying on product respiration to remove oxygen is fairly slow, and the product storage life can be increased if the oxygen is removed faster. Some operations purge the CA room with nitrogen, purchased in liquid form or produced on site. One type of nitrogen generator uses ammonia in a combustion process to consume oxygen and produce nitrogen and water. Two other systems use a molecular-sieve process (pressure-swing adsorption system) or semipermeable membrane to remove oxygen. Machines that remove oxygen by combustion of natural gas or propane all produce carbon dioxide, which must be removed by another process. Incomplete combustion in these machines has caused explosions in CA rooms and carbon monoxide poisoning of workers.

3.4.12 Monitoring Equipment

Oxygen and carbon dioxide levels must be monitored daily to ensure that they are within prescribed limits. Traditionally, operators have used a time-consuming wet-chemistry system. Automatic equipment now is used widely. It is more accurate than the traditional system, provides a log of the data, and can be connected to a controller to maintain proper gas concentrations automatically.

Temperature also should be monitored regularly. A minimum of two calibrated dial thermometers should be installed in each room. One should be near eye level, with the

dial located on the outside of the room. The other should be above the fruit and readable through an observation window near the ceiling. Electronic thermometers allow easier observation of room temperature, and the data can be printed out easily for a permanent record of operating conditions. Most new storages in the United States use four probes (or more) per room. Some probes also can be placed into bins to monitor fruit temperatures.

3.4.13 Safety Considerations

The atmosphere in CA rooms will not support human life, and people have died of asphyxia while working in CA rooms without breathing apparatus. A danger sign should be posted on all doors. The access hatch in the door should be large enough to accommodate a person equipped with breathing equipment. At least two people with breathing equipment should work together at all times, one inside and one outside the room watching the first person. The room must be thoroughly purged with outside air before entering without self-contained breathing apparatus.

3.4.14 Refrigeration Equipment

Refrigeration equipment for CA facilities is the same as for any other cold storage operation. Most CA storages are designed to maintain 0°C at 95% relative humidity.

References

1. Dellino, C. V. J., ed. 1990. *Cold and Chilled Storage Technology*. New York: Van Nostrand Reinhold.
2. American Society of Heating, Refrigeration, and Air-Conditioning Engineers. 1986. *ASHRAE Handbook Series* (4 books). Atlanta, GA: Author.
3. Kroca, R. W., and M. L. Hellickson. 1993. Energy savings in evaporator fan-cycled apple storages. *Appl. Engrg.* 9:553–560.
4. Stoecker, W. F. 1988. *Industrial Refrigeration*. Troy, MI: Business News.
5. Stoecker, W. F. 1995. *Industrial Refrigeration*, vol II. Troy, MI: Business News.
6. Thompson, J. F., F. G. Mitchell, T. R. Rumsey, R. F. Kasmire, and C. H. Crisosto. 1998. Commercial cooling of fruits, vegetables and cut flowers. University of California DANR publication 21567.
7. Thompson, J. F., and R. F. Kasmire. 1981. An evaporative cooler for vegetable crops. *Calif. Agric.* 35(3&4):20–21.
8. Wilhelm, L. R. 1979. Forced ventilation cooling of commercial snap bean shipments. ASAE paper no. 79–6518, St. Joseph, MI: ASAE.
9. Thompson, J. F., and M. Spinogolio. 1996. Small-scale cold rooms for perishable commodities. University of California Division of Agriculture and Natural Resources Leaflet 21449.
10. Waelti, H., and J. A. Bartsch, 1990. Controlled atmosphere storage facilities. In *Food Preservation by Modified Atmospheres*, ed. M. Calderon and R. Barkai-Golan, pp. 373–389. Boca Raton, FL: CRC Press.

3.5 Processing of Fruit and Vegetables

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3.5.1 Processing Options

A very wide range of techniques is applied to the processing of fruit and vegetables. Some commonly are used for many types of horticultural produce; a few techniques are unique to one or two types only. It must also be remembered that by various processes (sometimes integrated, sometimes not) one type of fruit or vegetable may yield many different products. Thus mangoes can be canned, dried, frozen, or made into puree, sauce, chutney, pickles, concentrate, jam, edible “leather,” beverages, nectar, and panna. Papaya provides jam, pickles, chutney, nectar, toffee, pectin, and also papain, an important protein-hydrolyzing enzyme used in the pharmaceutical, textile, paper-making, food, and animal-feed industries. Coconut can be processed to produce oil, milk, cream, desiccated coconut, pie fillers, soft cheese, meal, jam, soap, vinegar, nata de coco, toddy, and additives for lubricants and printing inks; the husk and shell can yield fiber and activated charcoal. Because of the large number of products, there is insufficient space here for a comprehensive treatment. This section therefore describes briefly the more common processes and those processes that pertain to some of the more significant products.

3.5.2 Blanching and Lye-Solution Treatment

Blanching is a process that almost always is carried out prior to canning or freezing vegetables. It also is used for a few types of fruit. It involves dipping the vegetables or fruits into boiling water or suspending them in steam for 1.5 to 3 minutes. This process can achieve a number of objectives. First, it kills microorganisms on the surface and in the case of green vegetables destroys the catalase enzyme and inhibits the peroxidase enzyme, both of which can produce off odors and flavors in storage. Second, it removes air from intercellular spaces (assisting in the formation of a head-space vacuum in cans) and softens tissues to facilitate filling containers. Sometimes, nutrient losses during steam blanching are reduced by a preconditioning (drying) process in which the food is exposed to warm air at 65°C [1]. Blanching may or may not help to preserve the color in green vegetables. Sometimes, blanching should be done at temperatures below 100°C. For instance, spinach blanched at 100°C loses some color, but when it is blanched at 77°C for 6 minutes, its color is fixed and is retained even after subsequent heating to 100°C. Blanching also is used to crack and loosen the skins of tomatoes, sweet potatoes, and beets prior to peeling.

Boiling lye solution (0.5%–1.5% sodium hydroxide) is used as a more vigorous means of peeling and cracking skins. Prunes are prepared by dipping in lye solution for 30 seconds to crack skins in order to facilitate drying. Peaches are peeled by immersion in lye solution for 1 to 2 minutes, while potatoes are immersed for 6 to 8 minutes. In both cases, this is followed by blanching.

3.5.3 Canning

Almost every type of fruit and vegetable is canned somewhere in the world, and in industrialized societies the canning process is associated with processed fruit and vegetables perhaps more than any other. In the case of some crops a greater tonnage is canned than is eaten fresh. For instance, in the United States over 50% of the peach and apricot crop is canned, and the same can be said of the bean crop in Europe. Most of the pineapple produced in a number of countries goes into cans. Canning is extremely valuable, because it enables fruit and vegetables of the customer's choice to be consumed year-round without the need for refrigeration. It also allows products to be exported that could not be exported in fresh form due to transport limitations or quarantine regulations. Because the can prevents the reentry of microorganisms completely, the life of the product (even at ambient temperature) can be several years, provided the integrity of the seal is maintained. In addition to the packaging of the sliced or whole product, canning also is used as a means of packaging purees, nectars, juices, and beverages.

The canning process involves cutting, washing, blanching, and then hot-loading into the can (which is usually made from tin-plated steel), which is then sealed. The can is then held at a prescribed temperature for a given time to ensure that all microorganisms are killed, before being quickly cooled. Some products are semicooked before canning; others receive only the blanching or heat treatment to bring them up to the filling temperature for canning (typically 85°C). After the can is sealed, it is heat-treated, usually by immersion in boiling water or in a pressurized steam retort [2].

3.5.4 Freezing

Freezing is a very popular and effective means of preserving many types of vegetable and needs little description. Prior to freezing, vegetables are normally blanched. Although some cut and sliced fruits are frozen commercially (e.g., apricots), freezing is generally not very effective for cut fruit because the fruit is susceptible to browning and oxidation upon exposure to air. However, some whole fruits such as berries are frozen satisfactorily.

3.5.5 Dehydration and Desiccation

Drying and Sulphuring

Drying is one of the oldest food processing and preservation techniques known to man. Dried fruits in particular constitute a large and growing industry worldwide. The essential feature of the process is to reduce the moisture content to a point at which enzymatic or microbial damage no longer occurs.

Fruits (e.g., apricots, peaches) are halved and pitted and then laid out by hand on wooden or plastic trays. Before they are placed in the sun to dry, or put into a high-temperature drier, many fruits are first treated with sulphur dioxide, a process known as *sulphuring*. The SO₂ taken up by the fruit displaces the air from the tissue, softens cell walls so that drying occurs more easily, destroys enzymes that might darken the color, and actually produces some color enhancement. The SO₂ usually is produced by burning

sulphur at the inlet to a sulphuring chamber or cabinet in which the trays are stacked. Most countries prescribe legal limits for the level of SO₂ in dried fruits, commonly 2000 mg per kilogram (2000 ppm). With some varieties of plums, it is necessary to allow some initial “wilting” in the shade before exposing them to strong sunlight, to avoid “boiling.”

In the case of solar drying, a moisture content of 15% normally has to be achieved before the product can be packed. High-temperature drying is an alternative, or a combination of the two often is used. For instance, in the case of apricots, one day’s exposure to the sun prior to high temperature drying at 50 to 60°C can be beneficial in imparting a sun-dried appearance.

To maintain maximum quality, dried fruits should preferably be stored at 10 to 15°C. Prunes are one product that is stored in the dry condition and later rehydrated for sale. The prunes are immersed in boiling water and packed into sealed plastic pouches at a temperature not less than 82°C before cooling.

Freeze-Drying

In freeze-drying, the product is first frozen and then placed in a vacuum-tight enclosure and dehydrated under vacuum with careful application of heat, the pressure being kept substantially below 4.6 mm of Hg. The process has a number of advantages. First, there is no reduction in volume, and as a result little change of appearance compared with atmospheric drying. A further major advantage is that much more of the nonaqueous volatile constituents, flavors, and so forth are retained. Freeze-dried foods also rehydrate more rapidly than other dried foods. Although many vegetables can be freeze-dried, one disadvantage is that freeze-dried vegetables are more susceptible to oxidative deterioration than air-dried vegetables. A further disadvantage of this method of drying is the capital cost of the equipment. The overall cost of freeze-drying is around four times that of conventional drying [1]. Certain fruits have been freeze-dried, such as papaya.

Desiccation

Desiccated coconut is a major product used in the confectionary industry as a bulking material. Fresh coconuts are shelled whole and the outer brown skin or testa pared off with a knife. The coconut water is drained away and the flesh is cut and washed and then sterilized in boiling water or in steam blanchers at 88°C for 5 minutes [3]. The pieces then are shredded into a fine wet meal in a hammer mill and dried to 25% to 30% moisture content in a steam-heated counterflow multistage drier at 77 to 82°C for 40 to 45 minutes. Finally, the product is size-graded and packed.

3.5.6 Controlled Ripening and Degreening

A number of climacteric fruits, notably bananas, mangoes, papaya, pears, tomatoes, and avocados are picked relatively green and are subsequently ripened by introducing ethylene or acetylene gas, calcium carbide, or smoke. One advantage of this approach is that it allows the fruit to be picked in the green mature state when it is less susceptible to mechanical damage due to handling and transport. Controlled ripening also ensures that a particular batch of fruit is more even in ripeness and color. A third advantage of

artificial ripening is that it can be done close to the market, ensuring that the fruit is sent to the retail outlet undamaged and at optimal ripeness.

The fruit to be ripened ideally is placed in an airtight ripening room maintained at a constant temperature (18–21°C for most fruits, but 29–31°C in the case of mango). There are two methods of exposing the fruit to ethylene. The trickle method involves trickling the ethylene gas into the room so as to maintain a concentration of 10 μL per liter, usually for a period of 24 hours. During this time relative humidity is maintained at 85% to 90%. The second method involves giving the room a single initial charge of ethylene to a concentration of between 20 and 200 μL per liter. The room then is ventilated after 24 hours to prevent carbon dioxide exceeding a 1% concentration, which would retard ripening. Rooms that are poorly sealed sometimes require a second charge after 12 hours. In modern practice, the fruit are packed in vented cartons stacked on pallets, and fruit temperature is controlled by forced air circulation as in a cooling facility.

More traditional rural methods of ripening bananas and mangoes involve putting the fruit into a pit in the ground or into a heap on the surface and covering with a tarpaulin or branches. In some cases ripening is induced by placing small sachets of calcium carbide among the fruit, which in the humid atmosphere produces acetylene. Acetylene has a similar effect to ethylene but is required in at least 100 times the concentration. Another frequently used technique is to expose the fruit to smoke produced by burning leaves or wood. Ethylene thereby is produced as one of the products of incomplete combustion. However, product quality may be reduced by this procedure, especially if immature fruit is used.

Controlled degreening sometimes is carried out on citrus grown in the tropics. Many citrus cultivars are mature before the green color disappears from the peel. The breakdown of chlorophyll and production of a rich orange color requires exposure to low temperature during maturation, and this explains why mature citrus frequently is sold green on markets in the humid tropics, where even night temperatures may not drop much below 25°C. Degreening is carried out in ripening rooms, with the same ethylene concentrations as above. The process may take 2 to 3 days, and it is again necessary to ventilate daily to ensure that carbon dioxide levels do not exceed 1%. The most rapid degreening occurs at temperatures of 25 to 30°C but the best color (concentration of peel carotenoids) occurs at 15 to 25°C [4].

Ripening and degreening also may be carried out by spraying with or brief immersion in an ethylene-releasing compound, such as ethephon.

3.5.7 Processing into Purees, Pastes, and Edible Leathers

Fruits such as tomato and mango are first peeled, destoned, and sliced, and the slices pulped in a homogenizer. The pulp then is sterilized by raising the temperature to at least 75°C (mangoes). The puree is then canned or sealed in polythene pouches for long-term storage and marketing.

Fruit “leathers” can be made by sun drying or forced-air dehydration of a puree layer on a thin plastic film. The dried product (typically from apricot or mango) has a bright appearance, good flavor, and a chewy texture. The end product is popular as a snack food.

3.5.8 Processing into Flour

A number of vegetable and fruit crops are used to produce flour, two of the major ones being soybean and coconut. Approximately 95% of the soybean crop is grown for processing. Most of this production goes into oil and high-protein flour. These high-protein concentrates and isolates are used as additives for nutritional enhancement (the important component being lysine, a particularly valuable amino acid). The concentrates also are processed further to produce soy milk and soy cheese and are extruded or spun to produce textured protein products for meat analogues.

Beans are first dried to 13% moisture content, cleaned, and then tempered by storing at 10% to 12% moisture content and 25°C for 7 to 10 days. This causes shrinkage, which assists in the subsequent cracking and dehulling stages. The dehulled beans then are conditioned by raising the temperature to 70°C, thereby increasing the amount of oil that can be extracted. The conditioned beans then are flaked by passing them through rolls, which produce flakes having a thickness between 0.25 and 0.38 mm. Oil then is extracted by the solvent process using hexane in a 1:1 ratio, the liquid being percolated through the bed of soy flakes. The flakes that are left contain 1% oil, 7% water, and 35% hexane. The hexane is recovered by passing the flakes through steam. This also serves to destroy antinutritional factors that are found in soybean, such as trypsin inhibitors. The flakes then are dried to 10% moisture content, toasted, and ground to a meal. Protein concentrates are prepared by removing the soluble carbohydrates by an aqueous-alcohol leaching process to give a product with 70% protein. Finally, isolates are produced by removing the insoluble carbohydrates with dilute alkali, yielding 96% protein [5].

Coconut flour is made by a number of processes. In the Yenko process, the mature nut is comminuted, then dried in a chamber at 80 to 100°C, and the oil removed in a press. The residual cake (at 1%–8% moisture) is ground into flour [3].

3.5.9 Juicing and Production of Nectars

Juicing is perhaps most typified by the citrus-processing industry, which produces juice, concentrate, and citrus oil (the latter being derived from the peel). Citrus concentrate is produced in very large quantities by many countries and is traded as an international commodity.

The juice first is removed by special extractors, being discharged with approximately 11° Brix (refractive index test for soluble solids) and a pulp content of 20% to 25% by volume. Downstream finishers (horizontally mounted screen drums) reduce the pulp content to 10% to 12% by volume. Centrifuges then are used to remove the trub particles to whatever extent the market requires. For the single-strength juice market, the resultant juice is pasteurized and bottled. For the concentrate market, this preclarified juice is passed through evaporators. It takes 10 to 12 ton of fresh fruit to produce 1 ton of concentrate with 65° Brix.

Frozen concentrate is considered to be a superior product, and it is made by concentrating juice under vacuum at room temperature to 56° Brix. Then 10% fresh juice is added and the liquid is quickly frozen to –20°C. The resulting concentrate of 44° Brix,

which retains the taste and aroma of fresh juice, can be kept for long periods and when used is diluted with three parts water [6].

To produce nectars, the fruits (typically peaches and apricots) are halved, pitted, peeled, and then cooked and passed through a disintegrator or pulper. After adding syrup and citric acid, the product is passed through a deaerator to prevent loss of color and flavor. When canned, the cans are held at 88°C for 3 minutes. If put into jars, the jars are sealed and pasteurized at 100°C for 20 to 30 minutes.

3.5.10 Aseptic Processing and Packaging

In contrast to canning, where the hot-filling and postsealing heat treatments are used to produce commercial sterility, in aseptic processing both the product and the packaging are made commercially sterile before the filling and sealing operations, and therefore no postsealing heating is necessary. The objective is a product that is stable for 2 to 3 months, and preferably for 6 months, without refrigeration.

Prior to packaging, the liquid or semiliquid product is heated quickly to a temperature at which it is commercially sterile and then cooled. The packages (e.g., coated cartons) are subjected to a combination of chemical and heat treatment. Preformed cartons usually receive a spray of hydrogen peroxide solution. Sometimes this is supplemented by ultraviolet irradiation. With many aseptic filling machines, as part of the process the carton is formed continuously from coils of waxed-paper packaging tube. The packaging material usually is dipped in a 35% hydrogen peroxide solution, and the surplus liquid blown off by a jet of hot air.

The economic advantages of aseptic processing and packaging lie in the use of packaging materials that are cheaper than metal cans and glass containers, the saving of heat energy, and the preservation of flavors. With aseptic systems, there is continuous flow of the product. Thus, with appropriate heat-exchanger design it is possible to raise and lower the product temperature more rapidly, allowing sterilization at higher temperatures. The higher temperatures are more effective in killing off relatively heat-resistant bacteria, while the shorter exposure time results in reduced loss of flavor, color, and nutrients [7]. This is sometimes known as high-temperature/short-time processing.

3.5.11 Minimal Processing for Retail and Fast-Food Outlets

Minimally processed fruits and vegetables are those that may have been cleaned, peeled, cut, sliced, and packaged in such a way as to retain their fresh appearance. They can be classed as “convenience foods,” typical examples being fruit slices, mixed-vegetable selections, coleslaw, shredded lettuce, and salads. Compared with other processes in which the product is made stable and is given a long shelf life, minimally processed fruits and vegetables are highly perishable. They are vulnerable to enzymatic and bacteriological breakdown and are therefore a health risk if not prepared and stored properly. Nevertheless there has been a growing demand for such products, with an annual market value of around US\$4000 to 8000 million in the year 2000. In some cases in which importation of fruit is prevented due to fruit-fly infestation, the importation of fruit segments may be possible, opening up a potentially large market.

Table 3.30. pH of some tropical fruits

	pH Level
Durian	6.7
Jackfruit	4.6–5.2
Mangosteen	3.0–3.2
Pineapple	3.5–4.0
Papaya	5.3
Pummelo	3.7–3.8

Source: [90].

Minimal processing poses a number of potential problems. Firstly, cutting and peeling allows substances such as the enzyme polyphenol oxidase within the cell to come into contact with the atmosphere, causing the well-known phenomenon of browning of the tissue. The release of sugar, acid, water, and so forth caused by cutting also provides a source of food for microorganisms to grow rapidly. This can be kept to a minimum by ensuring that knives are kept sharp. Removal of these substances by rinsing with fresh water or chlorinated water (200–300 ppm chlorine) is therefore recommended. Traditionally, sulphites have been used to inhibit browning, but these are now prohibited in many countries. Ascorbic acid has been used successfully in some cases. Sometimes microbial growth can be inhibited by the use of edible coatings [8]. In some fruits, lignification of the cut surface occurs as a natural response mechanism to protect the fruit or vegetable from microbial attack. This can change the appearance of the surface and result in adverse customer reaction.

Selection of the correct plastic packaging is very important, in order to minimize the aerobic respiration rate without leading to anaerobic respiration. To avoid condensation within the package, it is important that the product be cooled before being packed. Toxin-producing pathogens such as salmonella and listeria can present a potential problem, but this can be avoided by maintaining a pH of 4.6 or lower, at which the bacteria cannot multiply. Many tropical fruits naturally have a pH of less than 4.6, but durian, jackfruit, and papaya are exceptions (Table 3.30). Their preparation must therefore be done under especially hygienic conditions.

Modified-atmosphere packaging (MAP) plays a significant role in the life of minimally processed vegetables. Preservation systems that use MAP can give shredded lettuce a life of 11 to 15 days at 1 to 4°C, and cut florets of cauliflower and broccoli a life of at least 21 days [10]. Preserving *mixtures* of cut vegetables is generally more difficult than preserving single products. A particular treatment and MAP film may be optimal for one type of vegetable but may be less than optimal for another. Packages of mixed cut vegetables therefore may have a shorter storage life than those of their individual components. Although minimally processed products normally are associated with a short shelf life, some researchers claim that a number of fruits can be stored in sliced form for periods of 8 to 16 weeks in MAP at 1°C. It must be stressed that to achieve these storage lives, fruits were given very specific pretreatments before being sealed in their packages. A preservation procedure for cut and segmented fruit pieces has been developed [11]

that claims that sliced mango can be stored in MAP at 5 to 9°C for up to 12 weeks and papaya for up to 16 weeks—in the case of papaya, the fruit pieces were dipped in 5% citric acid and the package flushed with 15% to 20% oxygen and 3% helium balanced with nitrogen before sealing. A range of single films and film combinations is available for MAP, and a range of techniques is associated with them [12].

In the tropics, certain of the larger fruits such as durian (2–4 kg per fruit) and jackfruit (5–20 kg per fruit) are difficult or messy to open, and so they are traditionally cut open by the retailer and the pulp or fruit segments sold individually or in small trays. In the absence of MAP, durian pulp can be stored at 4°C for up to 40 days [13], and it is claimed that jackfruit segments can be stored successfully for up to 14 days at 5°C [14].

3.5.12 Fermentation into Alcoholic Beverages, Vinegar, Sauces and Other Products

Fermentation occurs naturally in the presence of bacteria, yeasts, and molds. Bacteria produce acids, which tend to act as preservatives; yeasts produce alcohol, which is also a preservative.

In addition to wine production from grapes (covered in a subsequent section) many fruits are fermented to produce alcoholic beverages, including apples (to produce cider), pears (to produce perry), bananas and a wide variety of berry fruits (to produce wines and liqueurs). Traditional alcoholic-beverage preparation relies on the naturally occurring yeasts and sugars to initiate the fermentation process. In commercial processing, these yeasts and other microorganisms first are controlled by treatment with sulphur dioxide, and the juice then inoculated with a chosen, desirable yeast culture. Care is taken not to expose the inoculated juice to the air during fermentation.

The most common type of vinegar produced from fruit material is cider vinegar. Apple juice is first fermented to form raw cider, after which it is clarified and allowed to stand for at least a month. Then in the acetification process, acetobacter bacteria and nutrient salts are added to produce a second (acetous) fermentation yielding acetic acid. In North America and the United Kingdom, the minimum legal strength for vinegars is 4% acetic acid w/v (weight in volume). Traditional methods of acetification employ the Quick packed generator, a container packed with beechwood shavings, providing a large surface area for the acetobacter to cover. Air circulates upward through the shavings, while the cider trickles down and is continuously recirculated. The conversion rate is about 1% every 24 hours. Faster production rates are achieved by employing a submerged culture fermenter (Frings type or tower type), in which air is continuously bubbled up through the must by a vortex stirrer at a rate of 100 to 250 L/min per 100 L of liquid [15]. Feedstock is added continuously at the bottom of the container and vinegar is drawn off at the top, making it a continuous process. Throughput is roughly double that of the packed generator for the same size. The vinegar is then clarified by filtering, diluted with water to 5% acetic acid, and pasteurized at 65 to 85°C before hot-filling into bottles or cold-filling into plastic containers.

Fermentation of legumes and legume–rice mixtures has been practiced in Asia and parts of Africa for centuries. The fermentation breaks down the carbohydrate to acid. One of the effects of fermentation is to make more of the nutrients available for assimilation in the form of amino acids, thus improving the digestibility of the legume protein. This

can make a significant difference to the adequacy of the diet for people who receive a low food intake.

In many countries, soybeans are inoculated with different types of bacteria, yeast, or mold cultures according to local tradition. Soy sauce (called *shoyu* in Japan) is a very popular sauce around the world but particularly in Asian countries. It is made by the initial fermentation of soybeans and wheat at fairly high salt levels for 72 hours, sometimes followed by a final slow fermentation over a 3-month period. In Indonesia, tempeh is made by fermenting soybeans with the rhizopus fungus. For almost two thousand years, koji has been made in China and Japan by fermenting soybeans with the aspergillus fungus.

3.5.13 Processing into Jams, Pickles, Chutneys, and Sauces

Four naturally occurring edible preservatives in very common use are sugar, vinegar, salt, and vegetable oil. Jams are made by boiling fruit in a sugar syrup until the liquid becomes relatively stiff. Sometimes additional pectin is added to cause the jam to set to a stiffer consistency upon cooling. The jam is poured into clean, sterilized containers while hot, sealed airtight, and then cooled. In some cases it also is desirable to cover the surface of the jam with a thin layer of wax.

Pickling of vegetables and unripe fruit (such as papaya and mango) usually involves some heating with the addition of spices, sugar, and other flavorings, followed by immersion in vinegar (acetic acid) or oil in glass jars. Onions, beetroot, and raw papaya slices usually are pickled in vinegar. Raw mango slices are pickled by first removing some of the moisture with salt, adding a partially ground mixture of spices such as coriander, fennel, cumin seeds, tumeric, garlic, and red chillis; and then putting them in jars and covering them with mustard oil.

Chutney is essentially a spicy jam and can be made from a range of fruit and vegetables, such as papaya, mango, apple, raisins, tomato, and onion. The ingredients are boiled together with spices and sweeteners, and maize and starch thickeners are added to make the product stiff upon cooling.

Powdered salt or brine is used to preserve some fruit and vegetables. Unpeeled raw mango slices can be kept in powdered salt in polyethylene pouches for 2 months, or alternatively in brine for 6 months.

3.5.14 Oil Production

Of the many types of oil that can be made from fruits, vegetables, and nuts, five are very significant in terms of world production and are traded as major commodities. In 1995 and 1996, of the nine major edible oils (in order: soybean, palm, rapeseed, sunflowerseed, cottonseed, peanut, coconut, palm kernel, and olive oil), soybean oil accounted for 28% (20 million metric tons), palm oil accounted for 21.9% (15.5 million metric tons), coconut oil accounted for 4.3% (3 million metric tons), palm kernel oil accounted for 3% (2.1 million metric tons), and olive oil accounted for 2.1% (1.5 million metric tons).

Soybeans are first processed as described previously to produce conditioned flakes having a large surface area. Oil then is extracted by the solvent process using hexane in a 1:1 ratio, the liquid being percolated through the bed of soy flakes. The *miscella* (oil and

solvent), which leaves through a mesh screen, contains 25% to 30% oil. This is passed through a two-stage evaporator, where steam-heated tubes cause most of the hexane to evaporate and then steam removes any residual solvent. The final liquid is 99.8% crude soybean oil. The oil then is passed through the further processing stages of degumming, neutralizing, bleaching, and hydrogenation to remove phosphatides, free fatty acids, iron, beta-carotene, and chlorophyll. Hydrogenation also improves the stability of the oil and raises the melting point, making it more suitable for the manufacture of margarine and shortening. The final stage is deodorization. In its simplest form, the process involves bubbling low-pressure steam at 170 to 230°C through the warm oil to remove volatiles. A more complex continuous process involves first deaerating the oil under vacuum and then passing it into a column containing a cascade of trays heated to 250°C by an upward countercurrent of steam. A steam ejector system maintains a pressure of 6 mm of mercury to enhance volatilization and protect the quality of the oil [16].

In the case of palm oil, bunches of palm fruits are sterilized with steam under pressure at 130°C in large horizontal tubular sterilisers for 40 to 60 minutes. The fruits then are stripped off the bunches in stripping machines of the beater-arm type or rotary-drum type. They are put into a digester, where they are heated to 95°C. About 50% of the oil is released at this stage and collected. The resulting mash leaves the digester and is passed through a screw press, which extracts the remainder of the oil. The crude oil is passed through screens, then through a heat exchanger that raises the temperature to 85 to 90°C, and finally into a clarification tank, where the oil rises to the top and a sludge is removed lower down.

Coconut oil is produced by a number of both dry and wet processes [17]. On large commercial scale, coconut oil is made from copra. Copra consists of large pieces of coconut meat dried down to a moisture content of about 6%. It usually is made locally on or close to the plantation and then collected and transported to the processing factory or exported for processing overseas. To make copra, fresh nuts or nuts harvested and stored for up to 4 weeks are dehusked and deshelled, either manually or by machine. They then are dried in one of several types of drier. Split into halves, they can be solar-dried or dried in a direct or indirect drier. In the direct drier, hot flue gases pass through the coconut, causing it to be smoked as well as dried. The smoke produces impurities in the final product but assists in preventing the growth of molds that are responsible for producing aflatoxins.

In large centralized oil mills, the copra is comminuted in a size reduction unit or hammer mill, heated, and then passed through a high-pressure single-screw or twin-screw expeller (pressure approximately 70 MPa). The extraction efficiency for the first pressing is 55% to 70%. In some plants the cake is passed through the press a second time. The residual oil present in the cake is removed by a solvent-extraction process, using hexane. Finally the oil is deodorized and refined.

A number of smaller-scale processes are used that by-pass the copra phase. Traditional methods involve the grating of fresh coconut meat and squeezing it to produce cream (a suspension of oil in water). The oil then is obtained by boiling off the water. Another method involves frying the grated meat on a hot plate to drive off the water before squeezing. More advanced biochemical methods involve the use of enzymes or bacteria

that react with the grated meat, causing quality oil, water, and protein extract to separate out after 48 to 72 hours. Superior-quality oil (with less than 0.2% free fatty-acid content) can be produced by using a moisture-assisted process, in which fresh grated coconut is dried down to 10% moisture content and pressed at low pressure (2–3 MPa).

3.5.15 Soaking to Remove Toxic and Indigestible Substances

Many legumes (e.g., soybean) contain antinutritional substances such as trypsin inhibitors, cyanogenic glucosides, alkaloids, saponins, and haemagglutinin which can cause stomach disorders. Cassava (manioc) contains small quantities of the glucosides linamarin and lotaustralin, which are converted to hydrocyanic acid (prussic acid) when they come into contact with the enzyme linamarase, which is released when the cells of roots are ruptured. These undesirable chemicals are rendered inactive or leached out by soaking in water, sometimes with the addition of heat.

3.5.16 Irradiation

Ionizing radiation treatment has four potential uses, namely the disinfestation of insect pests, extension of shelf life by retarding ripening and sprouting, inhibition of rotting, and disinfection of material affected by harmful organisms such as salmonella.

Although effective in dealing with insect pests, irradiation is not used for this purpose commercially on any significant scale, and it still is more expensive than alternative chemical and heat treatments. Irradiation currently is used mainly for inhibition of sprouting in potatoes and onions. At present Japan makes the widest use of irradiation for these products. Sprouting is inhibited by a dose of 0.02 to 0.15 KGy, and at this level it has little effect on sugar level, flavor, or texture. Because of the high capital costs, the process still is more expensive than inhibition using chemical treatments such as chloropham or maleic hydrazide. One unfortunate side effect in the case of potatoes is that irradiation at the levels used to inhibit sprouting also inhibits the light-dependent development of chloroplasts in the outer cell layers of the tubers. This can represent a hazard for the customer, because potatoes exposed to light in transparent bags continue to produce the harmful substance solanine but give no indication of this by showing no signs of greening.

Attempts to inhibit rotting and ripening of fruit by the use of irradiation and thereby to increase shelf life have met with limited success. It is claimed that rotting can be prevented in strawberry, tomato, and fig, and that ripening can be extended in banana, mango, papaya, and apricot [18]. However, the effect of irradiation on fruits varies not only among fruits but also from cultivar to cultivar. Irradiation extends the life of some cultivars of mango, for instance, but shortens the life of others. In some cultivars it prevents ripening altogether and can produce skin blemishes. Irradiation tends to produce an overall softening of fruit that is different from the selective softening that occurs during the natural ripening process [19]. Irradiation is used on a significant commercial scale for disinfection of a range of spices.

Health concerns, in particular the relatively unknown effects of free radicals and other chemical changes produced by the irradiation process, will continue to put limits on the application of irradiation to foods. Use of plastic packaging materials that are irradiated

at the same time as the product must be monitored carefully, because irradiation causes some plastics (e.g., PVC) to break down into toxic substances.

3.5.17 Equipment for Physical Processes (Unit Operations)

Size-Reduction Units

Chopping, cutting, slicing, dicing, julienning, and shredding are carried out with a range of cutting elements. Slicing is done by rotating or reciprocating blades as the product passes beneath. In the dicing operation, the material is sliced and then cut into strips by a series of rotating blades. The strips are then cut into cubes by a further set of knives acting in a perpendicular plane. Shredding is performed either by multiple rotating knives (in a machine similar to a hammer mill, but with the hammers replaced by knives) or in a squirrel-cage shredder, in which the product is made to pass between two contrarotating cylindrical cages, both fitted with knives.

Homogenizers and Colloid Mills

Homogenizers come in a number of designs. In pressure homogenizers, a high-pressure pump operating at 10 to 70 MPa feeds the liquid through a poppet valve with the poppet set to produce a gap of 300 μm . The rapid drop in pressure and sudden change in velocity produces turbulence that reduces the globule size. In some equipment, the high-velocity jet is made to impinge on a breaker ring to achieve a better result. A second type of homogenizer (used for ice cream, salad creams, and essential oil emulsions) uses ultrasonics. The dispersed and continuous phase of an emulsion are together pumped through an orifice with a pressure of 0.3 to 1.4 MPa, where they impinge on a metal blade that is made to resonate at 18 to 30 kHz. Resonance of the blade can be caused by the jet of fluid or by an electromechanical transducer.

Colloid mills are essentially disc mills, with one disc stationary and one disc rotating at 3000 to 15000 revolutions per minute. The small clearance between them (0.05–1 mm) produces high shearing rates and forces, as the fluid travels from the center to the outer periphery. Colloid mills are particularly suitable for high-viscosity liquids. The discs may be flat, conical, or corrugated or have other asperities on them that are suited to processing a particular material.

Juice Extractors

Two types of juice extractors are used. The first is a mechanized and automatic version of the standard kitchen lemon press, for which the fruit is cut in half and squeezed against a ribbed hemisphere. In the second type, the whole fruit is held between a lower and an upper cup, while cutters in the center of both cups begin to cut plugs in the fruit. Pressure then increases on the fruit, forcing the material through the bottom plug and into a prefinisher tube. The peel then is discharged between the upper cup and the cutter (see Fig. 3.35). The juice and juice sacks then pass through small holes in the finisher tube, while larger particles are discharged through the bottom of the tube.

Centrifugal Clarifiers

Clarifiers are used to separate solids from liquids. The simplest form of clarifier is the cylindrical-bowl type. The liquor to be clarified (usually with a maximum of 3% w/w

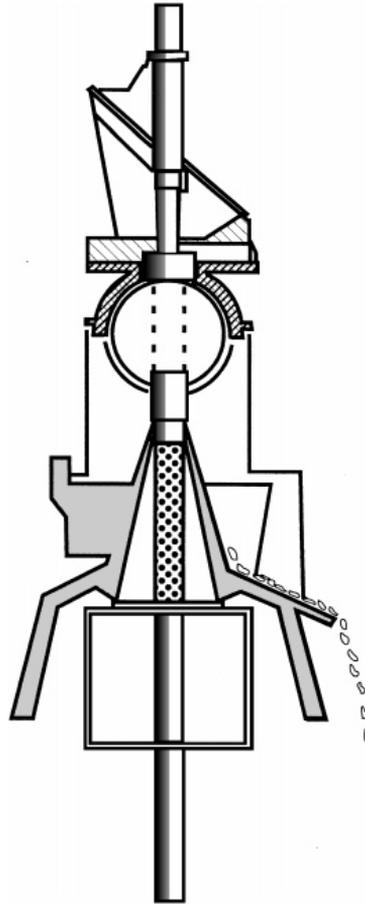


Figure 3.35. Juice extractor.

solids) is introduced into the bowl, and solids form a cake on the bowl wall. When the cake has built up to a given thickness, the bowl is drained and the cake removed through an opening in the bottom of the cylinder.

Liquors that have a higher solids content are clarified using centrifuges that have bowls of a biconical shape. They are of two types, nozzle centrifuges and discharge centrifuges. The nozzle type has small holes at the periphery of the bowl, through which solids are continuously discharged. In the valve type, the holes are fitted with valves. These valves periodically open for a fraction of a second to discharge the solids that have accumulated. Figure 3.36 shows a section of a biconical clarifier [20].

Filters

A very common type of filter is the plate-and-frame filter press (see Fig. 3.37). Cloth or paper filters are supported on vertical plates, a number of which are clamped together

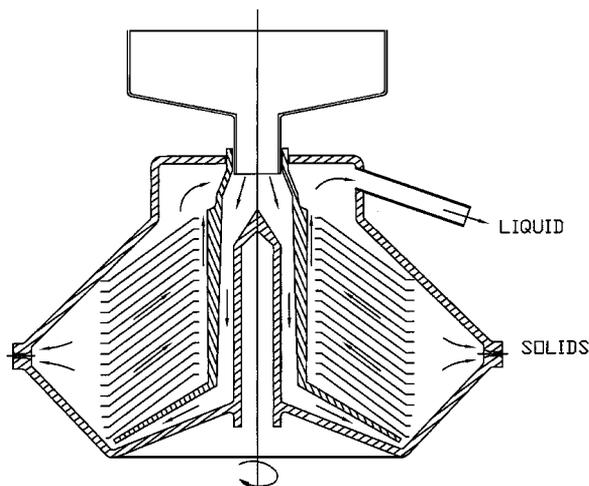


Figure 3.36. A section of a biconical clarifier.

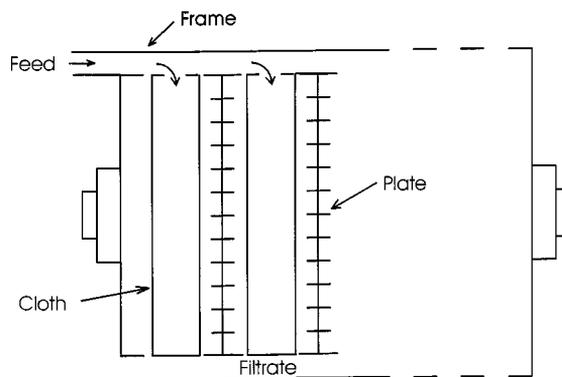


Figure 3.37. Plate-and-frame filter press.

depending on the filter capacity required. The feed liquor is pumped into the press under pressure. Having passed through the filter cloths, it flows down a number of grooves in the surfaces of the plates and drains out through an outlet channel at the bottom. As with all filters, as a bed of particles collects on the filter cloth, the pressure required to maintain the flow increases. Once the pressure has increased to a predetermined value, the plates are back-washed with water. To remove the cake fully, the press is dismantled, the plates cleaned, and the press reassembled. This is obviously a time-consuming operation.

Another type of filter is the shell-and-leaf pressure filter. It consists of meshing leaves, which are supported on a hollow frame. The mesh is coated with a filter medium. The leaves are enclosed in a pressure vessel. In some of the more expensive designs, the

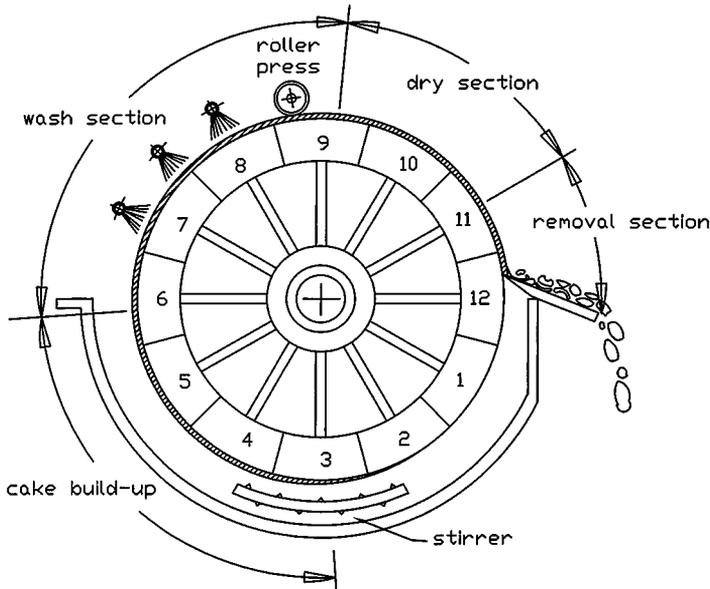


Figure 3.38. A section of rotary-drum vacuum filter.

leaves are made to rotate to even out the deposition of particles. Feed liquor is pumped into the pressure vessel, and solid particles collect on the filter medium. When the filter is choked with cake, the cake is blown off or washed from the leaves. Thus the cleaning is much less labor-intensive than for plate filter presses.

Rotary-drum vacuum filters are able to work continuously (see Fig. 3.38). They consist of a cylindrical drum that rotates slowly about a horizontal axis and is roughly 50% submerged in a bath of liquor. The drum is divided into a number of shallow airtight compartments, each compartment being covered in filter cloth and connected to a central vacuum pump. As the drum rotates, cake builds up. When the cake layer lifts out of the liquor, it is washed and drained. When each compartment reaches a certain position, the vacuum is removed and air pressure applied to loosen the cake. Finally the cake is scraped from the filter cloth on a continuous basis [1].

Presses

Ram Press

The ram press is a batch press, frequently used for small-scale oil extraction or grape-juice expression. Pulp or oil-bearing material is placed into a heavy-duty perforated metal cylinder or slatted cage and a pressure plate forced down onto the material by a screw or hydraulic mechanism. In some instances, the pulp or oil-bearing material is held in a cloth bag. Liquid flows through the perforations or slots and is collected.

Roller Press

Roller presses allow fruit pulp to be pressed on a continuous basis. The pulp passes between two heavy fluted metal rollers. The rollers also may be hollow and perforated.

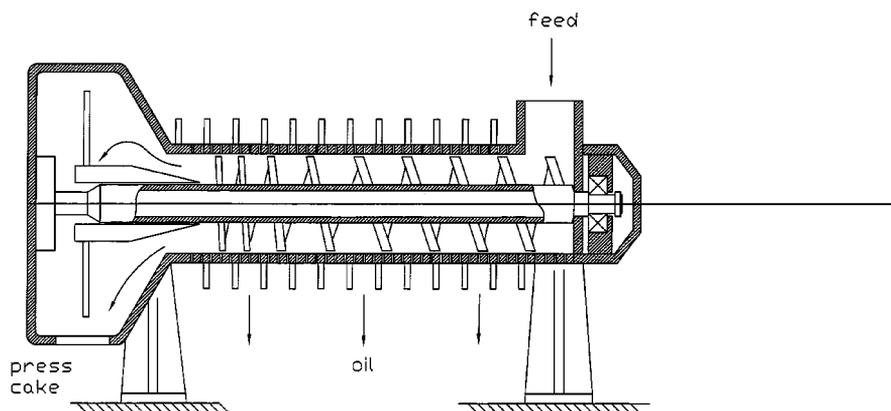


Figure 3.39. Section of screw press.

Juice is expelled along the flutes or through the perforations, while the cake is removed from the rollers by scraper blades. With this type of press, high pressures can be achieved if required.

Belt Press

A further development from the roller press is the belt press. The belt (normally plastic) passes over two stainless-steel cylinders, one of which is perforated. Fruit pulp is loaded onto the inside of the belt and is squeezed between the belt and the perforated cylinder. Juice is expelled through the perforations, while the press cake is scraped off the belt at the other end.

Screw Press (Expeller)

Screw presses consist of a stainless-steel helical screw inside a strong housing (Fig. 3.39). The pitch of the screw decreases towards the outlet end, resulting in a gradually reduced flow area and an increasing pressure applied to the pulp. Holes in the cylinder allow the juice or oil to escape. At the outlet end, the flow is choked by a conical plug that can be adjusted to vary the pressure exerted by the screw. The screw mechanism causes considerable friction, resulting in heavy power consumption and heating of the material. Higher temperatures usually improve oil-expelling efficiency by reducing viscosity, and so this heating is beneficial. Additional heating sometimes is used by wrapping electrical heaters around the cylinder. Some of the larger screw presses have twin, contrarotating screws.

Extruders and Extrusion Cookers

Extruders generally are similar to expellers insofar as they are normally of the single-screw or twin-screw type, demanding high energy input and sometimes generating considerable frictional heating. At the outlet, they have a die of the required shape, through which the material is forced, and then rotating knives (or a guillotine) cut the extrusion to the right length or shape. Thus strips, rods, tubes, spheres, doughnuts, squirls, and shells can be produced. Frequently the extruded material subsequently is sprayed with sugar solution or flavoring.

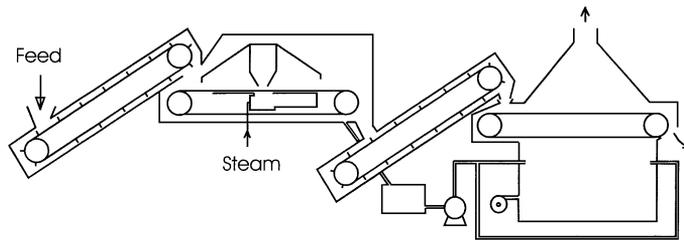


Figure 3.40. Continuous steam blancher.

In cold extrusion, the extruder has a deep-flighted screw that rotates at 30 to 60 revolutions per minute. It is used for soft, doughy material that produces little heat. Special dies can be made to inject a filling into an outer shell, a process known as *coextrusion*. In extrusion cookers, the food is heated within the extruder by a steam-jacketed barrel or a steam-heated screw. The residence time is longer (30–90 sec). The rapid release of pressure as the material emerges from the die causes sudden expansion of steam and gas within the material, yielding a highly porous, low-density product.

3.5.18 Equipment for Thermal Processes (Unit Processes)

Blanchers

Blanching can be done by either a batch process or a continuous process. Figure 3.40 shows a sketch of a continuous steam blancher.

Steam-Heated and Water-Heated Kettles

Heating of liquids and slurries frequently is done using stainless-steel kettles, which consist of a hemispherical pan having a jacket around them through which saturated steam or hot water is passed.

Evaporators and Dehydrators

Open and Closed Pan Evaporators

These are essentially similar to the kettles described previously and can be steam-heated or heated by gas or electric heating elements. They are cheap but relatively energy-inefficient and labor-intensive.

Short-tube Evaporators

These are essentially tube-and-shell heat exchangers. The heat exchanger contains a vertical bundle of tubes inside a vessel or shell. Steam condensing on the outside of the tubes heats the feed liquor, which rises up through the tubes, boils, and recirculates through a central passage called a *downcomer*.

Long-tube Evaporators

These consist of a vertical bundle of tubes encased in a steam shell which can be up to 15 m high. Liquid is introduced into the evaporator at just below boiling point. Within the tubes, boiling commences and the expansion of steam forces a thin film of liquor along the walls of the tubes, rapidly concentrating as it goes. For heat-sensitive, viscous

liquids the feed is introduced at the top of the tube bundle. This type of evaporator is relatively energy-efficient, and it is widely used for citrus-fruit juices.

Other evaporator types include the external calandria type, forced-circulation type, plate type, expanding flow type, and mechanical thin-film evaporators [2].

Retorts and Sterilizers

Retorts are pressurized containers in which canned products are sterilized or heat processed. With this batch process, the cans are loaded into the retort in a special cage, and the retort sealed with a gastight lid. Saturated steam is introduced into the retort, and as it condenses onto the outside of the cans the latent heat raises the temperature of the contents rapidly. After heat treatment, cooling water is passed through the retort. Once the product temperature has dropped below 100°C, the pressure is released and cooling continues to 40°C.

Batch-type retorts have certain advantages but are labor-intensive. Continuous-pressure sterilizers are in use with capacities well above 1000 cans per minute.

Heat Exchangers

Plate Heat Exchangers

These are widely used for pasteurization of low-viscosity liquids such as fruit juices. They consist of a series of thin vertical stainless-steel plates held tightly in a rigid frame. The gaps between the plates form narrow channels, and alternate channels are connected together in parallel. The liquid to be sterilized is passed through one set of alternate channels, while the heating medium (steam or hot water) is passed in between. The inlets and outlets are arranged to form a counterflow pattern. Plates usually are corrugated to cause fluid turbulence, thereby reducing the thickness of the boundary layer and increasing the rate of heat exchange.

Shell-and-Tube Heat Exchangers

This type of heat exchanger frequently is used as an evaporator and is described in a previous subsection.

References

1. Fellows P. 1988. *Food Processing Technology: Principles and Practice*, pp. 201–209. VCH Publishers.
2. Brennan J. G., J. R. Butters, N. D. Cowell, and A. E. V. Lilly. 1990. *Food Engineering Operations*, 3rd ed., pp. 264–278. Elsevier Applied Science.
3. De Leon, S. Y. 1990. In *Coconut as Food*, ed. J. A. Banzon, O. N. Gonzalez, S. Y. de Leon, and P. C. Sanchez, Philippines Coconut Research and Development Foundation.
4. Wills, R. B. H., W. B. McGlassen, D. Graham, T. H. Lee, and E. G. Hall. 1989. *Postharvest: An Introduction to the Physiology and Handling of Fruit and Vegetables*. New South Wales University Press, pp. 117–118.
5. Norman, A. G., ed. 1978. *Soybean Physiology, Agronomy and Utilization*.
6. Salunkhe, D. K., and S. S. Kadam. 1995. *Handbook of Fruit Science and Technology*. Marcel Dekker.

7. Hotchkiss, J. H. 1989. Aseptic processing and packaging of apple juice. In *Processed Apple Products*, ed. D. L. Downing, pp. 189–212. Van Nostrand Reinhold.
8. Reyes, V. G., L. Somons, and C. Tran. 1995. Preservation of minimally processed carrots by edible coating and acid treatment. Proceedings Australasian Postharvest Horticulture Conference, Melbourne, Australia, September 1995, pp. 451–456.
9. Siriphanich, J. 1993. Minimal processing of tropical fruits. Proceedings International Conference on Postharvest Handling of Tropical Fruits, Chiangmai, Thailand, July 1993. Australian Centre for International Agricultural Research, Proceedings No. 50, Canberra, pp. 127–137.
10. Reyes, V. G., and I. V. Gould. 1995. Improved processing and packaging of selected minimally processed vegetables. Proceedings Australasian Postharvest Horticulture Conference, Melbourne, Australia, September 1995, pp. 445–450.
11. Powrie, W. D., R. Chiu, H. Wu, and B. J. Skura. 1990. Preservation of cut and segmented fresh fruit pieces. U.S. Patent No. 4,895,729.
12. Greengrass, J. 1993. Films for MAP of foods. In *Principles and Applications of Modified Atmosphere Packaging of Food*, ed. R. T. Parry. Blackie Academic & Professional.
13. Praditduang, S. 1986. Cold storage of durian. *Kasetsart Journal* 20(1):44–49.
14. Tonnanonta, M. 1992. Storage of jackfruit pulp. Undergraduate Special Problem, Department of Horticulture, Kasetsart University, Bangkok.
15. Downing, D. L. 1989. Apple cider. In *Processed Apple Products*, ed. D. L. Downing, pp. 169–187. Van Nostrand Reinhold.
16. Robbelen G., R. K. Downey, and A. Ashri. 1989. *Oil Crops of the World*, pp. 254–256. New York: McGraw-Hill.
17. Chavan, J. K., and S. J. Jadhav. 1995. In *Handbook of Fruit Science and Technology*, ed. D. K. Salunkhe, and S. S. Kadam, pp. 485–507. New York: Marcel Dekker.
18. Akamine, E. K., and J. H. Moy. 1983. In *Preservation of Food by Ionising Radiation*, ed. E. S. Josephson, and M. S. Peterson, pp. 129–158. Boca Raton, FL: CRC Press.
19. Murray, D. R. 1990. *Biology of Food Irradiation*, pp. 48–53. Research Studies Press and John Wiley & Sons.
20. Bott, E. W., and S. Scottler. 1989. Centrifuges, decanters and processing lines for the citrus industry. Technical-Scientific Documentation No. 14, Westfalia Separator AG, Oelde, Germany.

3.6 Fruit and Vegetable Postharvest Systems in the Tropics

C. J. Studman

3.6.1 Relevance of Postharvest Engineering for Fruit and Vegetables in the Tropics

Tropical countries can produce a wide range of food products that have the potential to supply both their domestic and overseas market needs [1]. As we move into the 21st century, there is every opportunity for producers to take advantage of the increasing

Table 3.31. Production of selected crops in 1993–1994 and 1984–1985 (in millions of tons except wine)

	Year	World Total	World Export	Developing Countries	
				Total	Export
Oranges	1984/5	40.2	3.57	27.3	1.57
	1993/4	53.8	4.40	36.4	1.27
Lemons	1984/5	5.1	0.92	2.8	0.25
	1993/4	7.5	0.98	5.0	0.34
Tangerines	1984/5	6.7	1.09	2.3	0.30
	1993/4	9.4	1.88	4.6	0.56
Grapefruit	1984/5	3.7	0.66	1.1	0.29
	1993/4	4.5	0.96	1.7	0.23
Wine (10 ⁶ hL)	1984/5	319.9	53.3	29.5	3.0
	1993/4	252.5	49.0	32.5	2.1
Tobacco	1984/5	6.2	1.4	4.1	0.75
	1993/4	7.7	1.66	6.1	1.04
Bananas	1984/5	—	6.78	—	6.34
	1993/4	113.0	28.7	71.9	17.5
Coffee	1984/5	5.8	3.92	5.8	3.9
	1993/4	5.4	4.7	5.4	4.4
Rice	1984/5	470.0	11.4	444.0	8.6
	1993/4	531.8	15.7	502.8	12.3
Wheat	1983/4	513.3	—	207.7	—
	1993/4	534.8	93.0	250.1	9.0
Tea	1984/5	2.2	0.94	1.9	0.94
	1993/4	2.6	1.14	2.4	1.14
Coarse grains	1984/5	857.8	—	285.3	—
	1993/4	885.1	83.0	339.0	17.5

Sources: [4, 5].

demand for a range of quality food products. Developing markets for tropical crops that are unknown in developed countries offers tropical countries a great opportunity to take advantage of the current desire for a wide variety of healthy foods. For example, such crops could include baobab, wild mango, African fan palm, African ebony, breadfruit, tamarind, wild loquat, feijoa, tree mallow, starfruit, jackfruit, and soursop [2, 3]. World production levels of some crops are given in Table 3.31. This table indicates the rapid growth in fruit sales, compared with more traditional products. Vegetable production follows a similar trend.

The principles and information provided in the earlier parts of this chapter apply equally well in the tropics as elsewhere. However, there are additional challenges. Specific postharvest engineering designs based on tropical conditions have been produced by a number of institutes and organizations, as discussed subsequently.

3.6.2 Crop Losses in the Tropics

Estimates of crop losses in the tropics vary dramatically from country to country. Although grain losses are put at around 25% in less-developed countries, wastage of fruit and vegetable crops has been estimated to be around 50% of production [1]. This is a huge

**Table 3.32. Percentage crop losses
in developing countries**

	Estimated Loss of Total Crop
Apples	14
Avocados	43
Bananas	20–80
Cabbage	37
Carrots	44
Cassava	10–25
Cauliflower	49
Citrus	20–95
Grapes	27
Lettuce	62
Papayas	40–100
Plantain	35–100
Potatoes	5–40
Onions	16–35
Raisins	20–95
Stone fruit	28
Sweet potatoes	35–95
Tomatoes	5–50
Yams	10–60

Sources: [6, 7].

loss and represents an enormous waste of resources and opportunity. In contrast, losses in developed countries are generally around 10% to 25%. Examples are given in Table 3.32.

There can be many reasons for losses. The existence of and access to a suitable market outlet at an economic price, knowledge of postharvest principles, available storage facilities, availability of labor, good handling systems, and good product management are all essential components of the successful utilization of fruit and vegetables, and only if all these factors are present can losses be reduced significantly. Good postharvest practices can reduce losses substantially, but implementation requires good education, good systems, good management, and the availability of resources. Preharvest practices are discussed elsewhere [6, 8].

3.6.3 Marketing Issues for Less-Developed Countries

Fruit and vegetables contain most of the mineral and vitamin needs for humans. By reducing postharvest losses, there is the potential to almost double the nutritional supply without another green revolution, and without further additions of fertilizer, irrigation, or even land area.

However, political and sociological factors may determine whether a producer wishes to become involved in these markets. There is a considerable risk factor, and producers must consider the balance between risk and return.

On the domestic market there are a number of challenges and pitfalls, particularly in marketing quality products [9]. Projects involving government-fixed pricing, food

processing of surpluses, mechanization, national grading standards, long-term storage, high-quality handling and packaging systems, and government-run operations all have resulted in costly failures at times in less-developed countries [9]. Improving quality will be successful only if there is a potential market able to pay higher prices for quality products. Local domestic markets may not recognize the nutritional value of fruits and vegetables [9–18]. Competitors may force prices down below economic levels.

In addition, the international marketplace is highly competitive, and returns in one year cannot be guaranteed the next year. Suppliers are dependent on the marketing infrastructure in the overseas market, and this requires investment and expertise. Consumer preferences can be affected by adverse advertising arising from relatively minor failures of quality-control systems somewhere in the postharvest chain, and the failure may be outside the control of the producer. Marketing chains require guaranteed supplies of quality product, which is a challenging demand for any biological product for which yield is related to uncontrollable factors such as climate, rainfall, pest incidence, and any other disturbances to the production cycle, including political and sociological factors. Growers and producers normally must place the importance of providing quality product for the international market above the needs of the domestic market. The local market may become the outlet for second-grade product. However, as the industry strives to meet international standards, the overall quality of product has to improve, so domestic market quality also can benefit from international marketing.

3.6.4 Engineering Challenges to Postharvest Systems in the Tropics

Temperature

As discussed earlier, temperature is one of the major factors in quality loss after harvest. It is essential to cool fruit and vegetables as quickly as possible to the lowest temperature they can sustain without chilling injury (see Section 3.2). Unfortunately, many tropical products begin to experience this physiological disorder at around 10 to 13°C, and so this sets a lower limit to the storage temperature. Values of recommended storage temperatures are listed in the Appendix, Table 3.A3. There has been some evidence to suggest that in some fruits, chilling injury can be reduced by an initial hot-water treatment (a few minutes in water at around 45°C) [19, 20]. This may enable storage of fruit at lower temperatures. For some products, particularly local cultivars of tropical fruit and vegetables, storage and handling requirements are unknown.

Where conventional refrigeration systems are available these should be used (see Section 3.4). In some regions, cool stores may need to be designed to allow for lengthy mains power failures. Back up power generation also may be needed. In many less-developed countries, most producers do not have access immediately to sufficient cool-storage space. Traditional home-storage methods should not be ignored, as these have evolved from practical experience with the particular crop cultivars grown in the region and are tuned to the local environmental conditions [2, 3, 18, 21–26]. However, the treatments may be cultivar-specific, and modification may be necessary for new varieties.

Some vegetable crops (mainly root crops) have appreciable periods of dormancy before the normal aging process continues. Yams, potatoes, beets, carrots, and onions can be stored for lengthy periods without cool storage, although the extent depends on the

cultivar. Some are best left in the soil, where temperatures are cooler, providing the soil is not too wet and the crops are protected from attack by animals. Onions and garlic can be stored hung up using twine in shaded areas. Other vegetables, such as peas and beans, can be dried. Leafy vegetables, including brassicas, fruits, and other vegetables deteriorate rapidly after harvest, and preservation processes such as sun drying or domestic processing using sugar, brine, or vinegar are effective. Fermentation processes also can be used to preserve cabbage, breadfruit, radishes, cassava roots, taro, and green bananas. Some fruits can be sun-dried (e.g., coconut copra, herbs, and spices).

Options for reducing temperature without conventional refrigeration are described in the following subsections.

Ventilated Stores

Suitable for crops with long storage lives, these should be built where the night-time air temperature is low during the storage period, and where the best breeze can be found. The building should be orientated to make use of the breeze as much as possible. If night-time temperatures are very low, hot-air in-flow during the day can be reduced with louvres or screens. The roof and walls should be well insulated: Grass thatch materials also can be wetted to produce evaporative cooling. Alternatively, white paint on exterior surfaces reduces absorption of heat. Double-skinned walls also are better than single-layer walls. Ventilation between walls and roof and under the floor also is needed [24–26].

Root crops can be stored on the ground in simple clamps, consisting of a long triangular pile of the product 1 to 2 m wide, covered by straw and soil layers, and with adequate provision for water run-off. Ventilation also is provided by making a triangular open channel at the base of the pile in the center and running the length of the pile. This central duct may need vertical chimney vents at regular intervals (see Chapter 2).

Local Features

Caves can be used in regions in which they remain cool throughout the storage period. Fruit and vegetables can be stored longer if they are kept in stores on high ground, where air temperatures are lower. Cold running water also can be used to remove heat.

Postharvest Procedures

Keeping crops cool can be achieved by very simple means. If crops are harvested just before the sunrise they will be at their coolest. Once harvested they should be kept out of the sun. Thus, in the field harvested products should be placed in the shade at all times. They should be covered during daytime transportation, and trucks should not be parked in the direct sun. In the marketplace fruit and vegetables also should be shaded. Although obvious, these practices often are not followed. Products also require ventilation, as they generate heat internally, and unless this is removed continuously, the temperature will rise and deterioration will be accelerated.

Handling, Packaging, and Transportation

The same issues apply to tropical products as any other fruit or vegetable (see Section 3.3). Good packaging and careful handling increase the storage life of most crops and reduce damage. However, in less-developed countries problems can be exacerbated by

ignorance and cost-cutting. Roads can be very rough and delays common. Distances can be great and packaging minimal. In many markets it is considered uneconomical or impractical to use packaging, and so a high level of damage is accepted. Packaging can be produced from local biodegradable materials [6]. Options include bags, sacks, and woven baskets, but these offer little protection for the product. Wood boxes provide some protection but may not be acceptable on international markets. Cardboard or plastic containers also may be available (see Section 3.3). It also is possible to use secondhand containers if these are available locally.

Grading Systems

Simple off-floor grading systems are recommended for less-developed countries [8, 10]. In less-developed countries the majority of handling is likely to be done by hand, with limited options for mechanized systems. Machinery for automatic sizing and weighing may be appropriate, but because humans are generally better at sorting fresh produce for quality, low-cost labor can be an advantage.

Storage Systems

Modern and traditional storage systems have a continuing role to play in the tropics. Modified designs of traditional structures can greatly reduce losses due to vermin and other pests. For many fruits and vegetables drying adds to storage life, and stores can be based on designs developed for cereals [21–28]. Pest management is a major issue [29–31].

Wholesale Markets

Wholesale-market designs for less-developed countries have been discussed by the United Nations Food and Agriculture Organisation [32]. In addition to the normal issues that arise in the design and siting of buildings, factors that may need special attention include the following.

Roads and Parking

Table 3.33 gives guidelines for roads and parking suggested by the United Nations Food and Agriculture Organisation.

Internal and External Lighting

This should be at a high level internally (500–1000 lux), using fluorescent tubes to minimize heat gain. Outside roads require only around 12 lux [32].

Mechanical Ventilation or Air-Conditioning

The environment inside a large wholesale market in the tropics can be very unpleasant. Fruit and vegetables are respiring, and loading and unloading vehicles produce much heat. Roof extractor fans and natural ventilation can reduce temperatures by 3 to 5°C [32].

Waste-Disposal System

An allowance of 5% to 10% of product turnover is needed. Local domestic systems may not be designed to cope with the volume involved, and so special arrangements are needed. Interchangeable containers offer a convenient way of dealing with waste. The

Table 3.33. Appropriate road-design criteria for wholesale markets

	Length (m)	Width (m)	Radius (m)	Gradient (%)
Roads				
Lane width		3.5		0.5–5
Minimum width (1-way)		7.0		0.5–5
Minimum width (2-way)		12.0		0.5–5
Maneuvering distance		8.0		
Outside curb curve: minimum			10.5	
Outside curb curve: preferred			15.0	
Solid waste turning vehicle space			18.0	
Loading bays (end-on): minimum	8.0	3.75		
Loading bays (end-on): preferred	12.0	4.0		
Access ramps				
Up ramp: minimum width and maximum slope		5.5		8.0
Up/down ramp: minimum width and maximum slope		7.0		6.0
Preferred minimum width and maximum slope		7.0		5.0
Vehicle lengths				
Pick-up/minibus	5.0	2.0		
Standard truck	8.5	2.5		
Articulated truck	15.0	2.5		
Truck with trailer	18.5	2.5		
Parking spaces				
Pick-up	8.0	3.65		
Truck	11.0	3.65		
Small car (minimum)	4.8	2.4		2.0–5.0

Source: [32].

containers are placed at strategic locations and collected by truck when full, or at set times, with an empty container delivered at the same time.

Water and Sewerage

Requirements for water and sewerage in markets are higher than in other buildings due to the requirements for cleaning. For a 10,000-m² market, a daily demand of 75,000 L is likely. This includes some produce washing and a 10,000 L allowance for cool storage. Sanitary requirements should be around 1 unit per 15 to 25 persons [32].

Roof Cladding

The cladding is likely to be a critical design component. It must be able to perform under the conditions of high humidity and temperature. It should have a low U-value (e.g., less than 0.85 W · m⁻² · °C⁻¹) to prevent heating from the sun.

3.6.5 Role of the Agricultural Engineer

If a farmer wishes to retain a subsistence level of farming, then the agricultural engineer's role is to advise and develop systems that allow this level of operation to work

in a totally sustainable fashion [14, 18]. As population density increases and land becomes more scarce, the need for improved efficiency will grow. Packaging and storage studies will need to focus on solutions that can be achieved on-farm with minimum external inputs.

If the decision is made to develop and market produce, the agricultural engineer must use his or her expertise to aid the industry with its development. Quality, safety, and reliability of product supply must be assured if overseas markets are to be secured and developed. These are major issues that cannot be ignored. Agricultural engineers and scientists need to be aware of the challenges and then seek to find their own solutions that are best suited to the local culture and society. This may be far from the traditional concept of the designer and builder of machinery. He or she is also likely to be involved in the following.

Quality Standards and Management

Establishing quality standards is a key component to any significant long-term improvement in the quality of products [33, 34]. Export standards can be the main driving force, although it is possible for local industries to establish their own grading standards (e.g., Appendix, Table 3.A1). Examples of standards include apple and kiwifruit quality manuals, which govern all aspects of fruit production including preharvest spraying, harvesting, time to cool after harvest, weight, and packaging requirements, as well as standards relating to color, shape, and appearance [35, 36]. The United Nations Food and Agriculture Organisation has produced a series of manuals designed to assist governments of developing countries to establish workable food control systems [16, 37–41].

Measurement Techniques

New measures that are nondestructive but indicate quality are likely to have a profound effect on the success of any crop (see Section 3.1).

Information Transfer

In tropical countries the postharvest infrastructure for many important crops is dependent on individual farmers and producers with limited resources. Even though postharvest researchers are becoming increasingly aware of the requirements for successful storage of commercially important food products, all too often systems are poorly designed or fail as a result of economic constraints, lack of knowledge, or inadequate quality-management systems to ensure that standards are adhered to. New packaging systems, such as modified-atmosphere storage, introduce new opportunities for extending the storage lifetime of products, but these require careful design and an understanding of the physiological aspects of storage (see Sections 3.2 and 3.4).

Food Processing

Development of simple and advanced processing techniques reduces losses, enables gluts to be managed without flooding markets with produce, and provides long-term food storage [2, 3, 16, 42–44]. In particular, Dauthy [42] has produced a manual of processing guidelines for less-developed countries.

3.6.6 Future Prospects and Challenges

There is a large number of crops, especially in less-developed countries, that bear edible fleshy parts or nuts of acceptable quality. These are largely harvested either from wild trees or seedlings nurtured in small plantings [1, 18, 45–47]. The economic potential of these crops has been recognized, especially as traditional fruit crops come under severe pressure due to increasing production and declining profits [48, 49]. Currently many such crops are produced only for domestic markets, where quality standards are often minimal or nonexistent [33]. In any country, poor quality-control standards for produce result in unfavorable competition with foreign produce, even on the domestic market. For example, currently most less-developed countries suffer trade deficits on fruits and vegetables [50]. The development and implementation of relevant quality standards would enable produce to be traded more competitively in international markets. It has been argued that less-developed countries could increase their share of the world fresh-produce market “if the necessary standards were met” [50, 51]. Among these, food safety will be increasingly important in the future.

Numerous studies of the introduction of new technologies to a society show how deeply interdependent are the technical, economic, political, social, and cultural factors involved in the process of technical change. Transformations in society and technology are at the same time cause-and-effect, and the ways in which societies adapt to these transformations are no more systematic than the technical system is static. Thus, the understanding and effective management of the process of technological change requires an approach involving the expertise and analytical skills of several disciplines from the engineering to the social sciences. It is also important to emphasise that less-developed countries should not be treated as a homogenous group, because particular strengths and weaknesses vary widely between countries.

Social Issues

There have been renewed concerns in both developed and developing countries about the introduction of technology into the third world on the one hand and the relatively low success rate of many development programs on the other. Technology cannot simply be transposed to developing countries: Too many socio-cultural and techno-economic factors can affect the situation [52]. For example, the success or failure of development-assistance programmes may depend on the level of trust created between the “donor” and “recipient” [53]. It now is generally agreed that those technologies most likely to be adopted by developing countries are those that are appropriate and acceptable. That is, in addition to operational and technical suitability, the technology must be profitable, affordable, and available [54], and sensitive towards cultural, social, and environmental issues.

Culture

Culture is the set of shared values, attitudes, and behaviors that characterize and guide a group of people. As a rule, less-developed countries tend to have more rigid social structures, stronger religious influences, very distinct gender roles, and a high diversity of languages. Certain practical implementation issues also may affect the development,

testing, evaluation, and application of quality-control practices in the fresh-produce industry of developing countries. The cultivation of horticultural crops follows a well-defined gender line in most developing countries, with the men active in the production and marketing of fruits, and the women predominantly engaged in vegetable production [51]. Similarly, religious beliefs cannot be ignored in determining the acceptability of new or improved technologies [17, 55]. The culture of the consumer also may not be understood by the supplier, so that the quality expectations of the overseas consumer may not be recognized or appreciated by the employee who is to grade the produce. This makes the training of staff and the adherence to quality standards particularly difficult.

Labor

Generally, skilled labor is scarce and unskilled abundant. Education levels are low in many less-developed countries, although some have achieved nearly universal literacy. Training for quality control can be hampered by a lack of basic education and the inability to understand the need for quality standards. However, much grading of fruit and vegetable produce relies on the human eye; with abundant labor it should be easier to select, train, and employ people in less-developed countries.

Infrastructure

The efficiency of transportation systems has a major impact on quality-assurance procedures. It is not uncommon to find that major roads are poorly maintained. There is often a high frequency of equipment breakdown due in part to unsuitable operating conditions. Repair and maintenance facilities may be inadequate, and power supplies may be irregular. Village blacksmiths are often the repositories of knowledge on local raw materials and manufacture of spare parts. As much as possible, manufacture of some or all equipment should be carried out in the developing country. In addition to providing for the participation of the population, local manufacture may further promote integrated social structure through the growth of industries associated with raw materials supply and marketing.

Good information on domestic and foreign supply and demand, prices, and quality is important for the successful export of fresh produce. Marketing constraints include a lack of information concerning quality requirements and packaging, poor quality of produce, and inadequate quality standards. The managerial implication of a lack of infrastructure is that the export enterprise must take on the burden of providing or improving its own infrastructure (e.g., establishing information networks, purchasing transportation systems).

Institutions

The political fluidity of some less-developed countries weakens the institutions of government. Bureaucracies are often technically weak and inefficient. They are frequently overstaffed, underpaid, and in some instances underqualified. The implications of this for postharvest quality are inefficient, slow, and costly government services that have the task of approving export shipments. Centralization of governmental decision making may prevent an export company from moving quickly in response to market

demand. There also may be a lack of flexibility in some educational institutions, that could or should be key players in training staff.

Sometimes, a quality attribute becomes less important and another, more important factor arises due to consumer preference and other competitive pressures. Alternatively, new or revised government regulations may dictate changes in quality requirements [56]. Activities of political pressure groups in overseas markets also may lead to sudden changes in quality specifications, particularly where a crop is perceived to affect environmental, health, or social structures. Structures and standards therefore must be able to react rapidly to market changes.

Management Structures

Both less-developed and developed countries need to ensure that there is a product quality–management component in agricultural-development programs. Individual farmers are unlikely to develop the grading, storage, and distribution systems for their produce that will be demanded by the international market. Cooperative systems may be able to make progress towards introducing quality-assurance systems, but in general many less-developed country farmers have demonstrated an innate resistance to participate in co-operatives [11].

In order to meet existing international standards so as to compete favorably in the sophisticated “world market” of fresh fruits and vegetables, managers should be kept fully aware of developments in international trading agreements and regulations. For example there may be considerable advantages in marketing by gaining ISO 9000 certification for quality-management procedures (see Section 3.1).

References

1. Acland, J. D. 1971. *East African Crops*. London: United Nations Food and Agriculture Organisation/Longman.
2. Lancaster, P. A., and D. G. Coursey. 1984. Traditional post-harvest technology of perishable tropical staples. *Agricultural Services Bulletin 59*. Rome: United Nations Food and Agriculture Organisation.
3. Bencini, M. C., and J. P. Walston. 1991. Post-harvest and processing technologies of African staple foods: A technical compendium. *Agricultural Services Bulletin 89*. Rome: United Nations Food and Agriculture Organisation.
4. FAO. 1995. Commodity review and outlook 1994–5. *Economic and Social Development series 53*. Rome: United Nations Food and Agriculture Organisation.
5. FAO. 1985. Commodity review and outlook 1984–5. *Economic and Social Development series*. Rome: United Nations Food and Agriculture Organisation.
6. Thompson, A. K. , 1996. *Postharvest Technology of Fruit and Vegetables*. Oxford: Blackwell.
7. *Post-harvest Food Losses in Developing Countries*. 1978. Washington: National Research Council, U.S. National Academy of Sciences.
8. Rice, R. P., L. W. Rice, and H. D. Tindall. 1987. *Fruit and Vegetable Production in Africa*. London: Macmillan.

9. Dixie, G. 1989. Horticultural marketing: A resource and training manual for extension officers. Agricultural Services Bulletin 76. Rome: United Nations Food and Agriculture Organisation.
10. FAO. 1986. *Improvement of Post-harvest Fresh Fruits and Vegetables Handling*. Bangkok: United Nations Food and Agriculture Organisation.
11. Grierson, W. 1991. HortTechnology and the developing countries. *Horttechnology* (Oct/Dec):136–137.
12. Kader, A. A. 1983. Postharvest quality maintenance of fruits and vegetables in developing countries. In *Postharvest Physiology and Crop Production*, pp. 455–470. New York: Plenum.
13. Thomson, A., and N. Terpend. 1993. Promoting private sector involvement in agricultural marketing in Africa. Agricultural Services Bulletin 106. Rome: United Nations Food and Agriculture Organisation.
14. FAO. 1992. Agricultural engineering in development-training and education programmes. Agricultural Services Bulletin 92. Rome: United Nations Food and Agriculture Organisation.
15. FAO. 1989. Utilization of Tropical Foods. Food And Nutrition Bulletin 47 (No. 1 cereals, 2 roots and tubers, 3 trees, 4 beans, 5 oil seeds, 6 spices, 7 fruit, 8 animal products). Rome: United Nations Food and Agriculture Organisation.
16. FAO. 1989. Quality control in fruit and vegetable processing. Food And Nutrition Bulletin 39. Rome: United Nations Food and Agriculture Organisation.
17. Solhjo, K. 1994. Food technology and the Bahai Faith. *Food Science and Technology Today*, 8(1):2–3.
18. Amos, N. D., L. U. Opara, B. Ponter, C. J. Studman, and G. L. Wall. 1994. Techniques to assist with meeting international standards for the export of fresh produce from less developed countries. Proc. XI1 CIGR World Congress, Milan, Italy, vol 2, pp. 1587–1594.
19. Li, M., D. C. Slaughter, and J. F. Thompson. 1997. Quality of Kensington mango fruit following combined vapor heat disinfestation and hot water disease control treatments. *Postharvest Biology and Technology* 12:273–284.
20. Lay-Yee, M., and K. J. Rose. 1994. Quality of Fantasia nectarines following forced-air heat treatments for insect disinfestation. *HortScience* 27:1254–1255.
21. Sode, O. 1990. Agricultural engineering in development: Design and construction guidelines for village stores. Agricultural Services Bulletin 82. Rome: United Nations Food and Agriculture Organisation.
22. Bodholt, O. 1985. Construction of cribs for drying and storage of maize. Agricultural Services Bulletin 66. Rome: United Nations Food and Agriculture Organisation.
23. de Lucia, M., and D. Assennato. 1994. Agricultural engineering in development: Post-harvest operations and management of foodgrains. Agricultural Services Bulletin 93. Rome: United Nations Food and Agriculture Organisation.
24. Cruz, J. F., and A. Diop. 1989. Agricultural engineering in development: Warehouse technique. Agricultural Services Bulletin 74. Rome: United Nations Food and Agriculture Organisation.

25. Kat, J., and A. Diop. 1985. Manual on the establishment operation and management of cereal banks. Agricultural Services Bulletin 64. Rome: United Nations Food and Agriculture Organisation.
26. FAO. 1985. Standardised designs for grain stores in hot dry climates. Agricultural Services Bulletin 62. Rome: United Nations Food and Agriculture Organisation.
27. FAO. 1984. Agricultural engineering of cold stores in developing countries. Agricultural Service Bulletin 19/2. Rome: United Nations Food and Agriculture Organisation.
28. Farm Electric Centre. 1989. *Grain Drying, Conditioning and Storage*. Stoneleigh, UK: Electricity Council, Farm Electric Centre.
29. FAO. 1994. Rodent pest management in Eastern Africa. Plant protection and production paper 123. Rome: United Nations Food and Agriculture Organisation.
30. FAO. 1981. Food loss prevention in perishable crops. Agricultural Service Bulletin 43. Rome: United Nations Food and Agriculture Organisation.
31. FAO. 1983. Food loss prevention in perishable crops. Agricultural Service Bulletin 92. Rome: United Nations Food and Agriculture Organisation.
32. Tracey-White, J. D. 1991. Wholesale markets: Planning and design manual. Agricultural services bulletin 90. Rome: United Nations Food and Agriculture Organisation.
33. Kader, A. A. 1983. Postharvest quality maintenance of fruits and vegetables in developing countries. In *Postharvest Physiology and Crop Preservation*, ed. M. Lieberman, pp. 520–536. New York: Plenum.
34. Kader, A. A. 1992. Postharvest technology of horticultural crops. Publication 3311, 2nd ed., University of California, Davis.
35. Enzafruit. 1996. New Zealand apple quality standards manual. Hastings, New Zealand: New Zealand Apple and Pear Marketing Board (Enzafruit International).
36. New Zealand Kiwifruit Marketing Board. 1996. *Kiwifruit Quality Standards Manual*. Auckland, New Zealand: United Nations Food and Agriculture Organisation.
37. Martin, P. G. 1986. Manuals of food quality control: The food control laboratory. Food and nutrition paper 14/1 Rev.1. Rome: United Nations Food and Agriculture Organisation.
38. Dhamija, O. P., and W. C. K. Hammer. 1990. Manual of food quality control: Food for export. Food and Nutrition Paper 14/6, Rev. 1. Rome: United Nations Food and Agriculture Organisation.
39. FAO. 1984. Manuals of food quality control: Food inspection. Food and Nutrition Paper 14/5. Rome: United Nations Food and Agriculture Organisation.
40. FAO. 1991. Manual of food quality control: Quality assurance in the food control microbiological laboratory. Food and Nutrition Paper 14/12. Rome: United Nations Food and Agriculture Organisation.
41. FAO. 1993. Manual of food quality control: Quality assurance in the food control chemical laboratory. Food and Nutrition Paper 14/14. Rome: United Nations Food and Agriculture Organisation.
42. Dauthy, M. E. 1995. Fruit and vegetable processing. Agricultural Services Bulletin 119. Rome: United Nations Food and Agriculture Organisation.

43. Werkhoven, J. 1974. Tea processing: 1974. Agricultural Services Bulletin 26. Rome: United Nations Food and Agriculture Organisation.
44. Russell, D. C. 1969. Cashew Nut Processing. Agricultural Services Bulletin 6. Rome: United Nations Food and Agriculture Organisation.
45. Wood, B. W., and J. A. Payne. 1991. Pecan: An emerging crop. *Chronica Horticulturae* 31(2):21–23.
46. Parmar, C. 1991. Some Himalayan wild fruits worth trial elsewhere. *Chronica Horticulturae* 31(2):19–20.
47. Harrison, P. 1987. *The Greening of Africa*. London: Grafton Books.
48. Menini, U. G. 1991. Potential and issues for collaborative action on tropical fruit research and development. *Chronica Horticulturae* 31(3):38–39.
49. Krezdorn, A. H. 1970. Teaching and research for tropical overseas horticulture. *Hortscience* 5(6):9–10.
50. Hutabarat, B. 1989. Issues and strategies for developing Indonesian horticultural subsector. *IARD Journal* 11(1&2):5–13.
51. Aubee, E. R. 1992. Prospects and constraints of Gambian horticulture. *Chronica Horticulturae* 32(4):59–60.
52. Pollard, S., and J. Morris. 1978. Economic aspects of the introduction of small tractors in developing countries: Towards a philosophy for small tractor development. *Agricultural Engineer* 33(2):29–31.
53. Opara, L. U. 1994. Report on New Zealand Trade Conference, Massey University, Wellington, New Zealand.
54. Opara, L. U. 1989. Computer-aided model for selective agricultural mechanisation in Nigeria, Nsukka. Proc. 13th Annual Conference of the Nigerian Society of Agricultural Engineers Paper 89/FPM/08. Zaria, Nigeria: NSAE.
55. May, B. A. 1988. Agricultural engineering in third world countries 1938 to 1988 (parts 1 and 2). *Agricultural Engineer* 43(3):83–92, 43(4):112–126.
56. Kramer, A. 1973. Impact of changing quality requirements. *Hortscience* 8(2):2–3.

Appendix

Tables 3.A1, 3.A2, 3.A3, and 3.A4 follow on next page.

Table 3.A1. Quality factors for fruits and vegetables

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Notes	
Fruits																										
Apple	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Apricot	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Avocado	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	17% to 20.5% dry weight of the flesh depending on cultivar
Blackberry	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Freedom from calyxis, shriveling
Blueberry	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Cherry	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Cranberry	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Date	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Freedom from black scald, fermentation
Dewbury	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Freedom from calyxis, shriveling
Grape	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Grapefruit	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Skin thickness, scars, pitting, rind staining, > 2/3 of surface showing yellow, 0.9 Gy, 6.40/5.7 Munsell color
Honeydew melon	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Kiwifruit	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Lemon	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	> 28% by volume juice, rind stains, red blotch shriveling, Freedom from stylar end breakdown
Lime	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Mandarin	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Split pits
Nectarine	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Insect scale
Olive	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Munsell color
Orange	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Split pits
Peach	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Black end
Pear	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Persimmon	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Tops: color, length, and straightness
Pineapple	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	

Plum/Prune	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	> 1.85% acid in juice, juice Munsell color 5 R 5/12 or darker
Pomegranate	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Quince	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	> 1/2 or >3/4 of surface showing red or pink color, attached calyx
Raspberry	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Strawberry	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Tangerine	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Vegetables																			
Anise	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Artichoke	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Stem length, compactness
Asparagus	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Straightness, diameter of stalks, percent green color
Bean	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Beet	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Bunched																			
Greens	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	No other kinds of leaves
Broccoli	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Stalk diameter and length, compactness, base cut
Brussel sprouts	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Freedom from burst, soft, or spongy heads
Cabbage	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Cantaloupe	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Netting, freedom from "wet slip"
Carrot	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Pithiness, woodiness, doubles, bad flavor or odor
Cauliflower	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Compactness
Celery	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Length of stalk, midrib shape
Collard greens	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Corn (green)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	Milky kernels, cob length, coverage with fresh husks
Cow pea	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
Cucumber	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	

(Cont.)

Table 3.A1. (Continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Notes	
Dandelion greens	*			*			*		*		*					*			*		*			*		
Eggplant	*		*	*	*				*											*		*				
Endive, chicory	*		*	*	*				*											*		*			*	
Garlic	*			*					*																	Curing, compactness, well-filled cloves
Horseradish roots	*		*	*	*				*				*							*		*				Freedom from hollow heart
Kale	*		*	*	*				*											*		*				
Lettuce	*		*	*	*				*		*									*		*			*	Tipburn, broken midribs, bursting
Melon (casaba/persian)	*			*				*										*						*		
Mushroom	*		*	*	*			*		*								*		*		*			*	Roots (if attached: firmness and freedom from damage)
Mustard greens	*		*	*	*			*		*								*		*		*			*	
Okra	*		*	*	*			*		*										*		*			*	
Onion dry	*		*	*	*			*		*										*		*			*	Doubles, bottlenecks, sprouting
Onion green	*		*	*	*			*		*								*		*		*		*	*	Bulb trimming
Parsley	*		*	*	*			*		*								*		*		*			*	
Parsnip	*		*	*	*			*		*			*					*		*		*			*	Yellowing and shriveling
Pea (fresh)	*		*	*	*			*		*								*		*		*		*	*	Freedom from sprouts, blackheart, greening; extent of missing or feathered skin
Pepper (sweet)	*		*	*	*			*		*								*		*		*			*	
Potato	*		*	*	*			*		*								*		*		*			*	
Pumpkin	*		*	*	*			*		*								*		*		*			*	
Radish	*		*	*	*			*		*			*					*		*		*			*	Pithiness
Rhubarb	*		*	*	*			*		*								*		*		*			*	Straightness
Rutabago	*		*	*	*			*		*								*		*		*			*	
Shallot (bunched)	*		*	*	*			*		*								*		*		*			*	
Southern Pea	*		*	*	*			*		*								*		*		*			*	

Table 3.A2a. Summary of mechanical tests for food materials

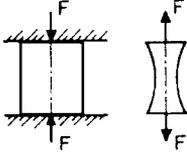
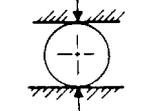
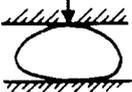
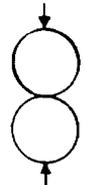
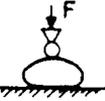
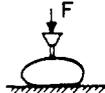
Type of Test	Parameter and Calculating Formula
<p>ASTM COMPRESSION OR TENSION</p> 	<p>ASTM compression or tension</p> $\sigma = \frac{F}{A}; \quad \varepsilon = \frac{\Delta L}{L}; \quad E = \frac{F/A}{\Delta L/L}$ $E = 3K(1 - 2\mu); \quad E = 2G(1 + \mu)$ $1/E = 1/3G + 1/9K$
<p>POINT LOADING</p> <p>PLATE ON SPHERE</p> 	<p>Point loading</p> $a = 0.721 m(FQd)^{1/3}$ $S_{\max} = \frac{0.918}{mn} \left(\frac{F}{Q^2 d^2} \right)^{1/3} = \frac{3F}{2\pi a^2}$ $D = 0.769k \left(\frac{F^2 Q^2}{d} \right)^{1/3}$ $E = \frac{0.338k^{3/2} F(1 - \mu^2)}{D^{3/2}} \left(\frac{4}{d} \right)^{1/2}$ $R_2 = R_2 = \infty; \quad R_1 = R_1' = d/2; \quad \cos T_k = 0;$ $m = n = 1; \quad k = 1.3514$
<p>PLATE ON CONVEX BODY</p>  <p>Deformation at bottom assumed negligible</p>	<p>Plate on convex body</p> $a = m \times 1.145 \left[\frac{FQ}{(1/R_1 + 1/R_1')} \right]^{1/3}$ $S_{\max} = \frac{0.365}{mn} \left[\frac{F}{Q^2} (1/R_1 + 1/R_1')^2 \right]^{1/3}$ $D = 0.485k [F^2 Q^2 (1/R_1 + 1/R_1')]^{1/3}$ $E = \frac{0.338k^{3/2} F(1 - \mu^2)}{D^{3/2}} (1/R_1 + 1/R_1')^{1/2}$ $R_2 = R_2' = \infty; \quad R_1 \neq R_1'$ <p>Values of m, n, k from eqn. 6.6 and Table 6.1 in Mohsenin [1] (Eqn. 1 and Table 3.A2b below)</p>

Table 3.A2a. (Continued)

Type of Test	Parameter and Calculating Formula
<p style="text-align: center;">SPHERE ON SPHERE</p> 	<p style="text-align: center;">Sphere on sphere</p> $a = 0.721 m \left[\frac{F Q}{(1/d_1 + 1/d_2)} \right]^{1/3}$ $S_{\max} = \frac{0.918}{mn} \left[\frac{F(1/d_1 + 1/d_2)^2}{Q^2} \right]^{1/3}$ $D = 0.769 k [F^2 Q^2 (1/d_1 + 1/d_2)]^{1/3}$ $E = \frac{0.338 k^{3/2} F (1 - \mu^2)}{D^{3/2}} (4/d_1 + 4/d_2)^{1/2}$ $R_2 = R'_2; R_1 = R'_1;$ $m = n = 1; k = 1.3514$
<p style="text-align: center;">SPHERE ON CONVEX BODY</p>  <p>Deformation at bottom assumed negligible</p>	<p style="text-align: center;">Sphere on convex body</p> $a' = \frac{an}{m}$ $a = 1.145 m \left[\frac{F Q}{(1/R_1 + 1/R'_1 + 4/d_2)} \right]^{1/3}$ $S_{\max} = \frac{0.365}{mn} \left[\frac{F}{Q^2} (1/R_1 + 1/R'_1 + 4/d_2)^2 \right]^{1/3}$ $D = 0.485 k [F^2 Q^2 (1/R_1 + 1/R'_1 + 4/d_2)]^{1/3}$ $E = \frac{0.338 k^{3/2} F (1 - \mu^2)}{D^{3/2}} (1/R_1 + 1/R'_1 + 4/d_2)^{1/2}$ $R_2 = R'_2; R_2 \neq R'_1;$ <p>Values of m, n, k from Eqn. 6.6 and Table 6.1 in Mohsenin [1] (Eqn. 1 and Table 3.A2b below)</p>
<p style="text-align: center;">DIE LOADING</p>  <p>Deformation at bottom assumed negligible</p>	<p style="text-align: center;">Die loading</p> $p = \frac{F}{2\pi a \sqrt{a^2 - r^2}}$ $D = \frac{F(1 - \mu^2)}{2a E}$ $E = F/D \frac{(1 - \mu^2)}{2a}$

(Cont.)

Table 3.A2a. (Continued)

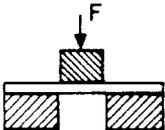
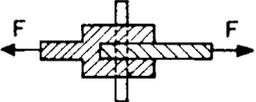
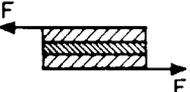
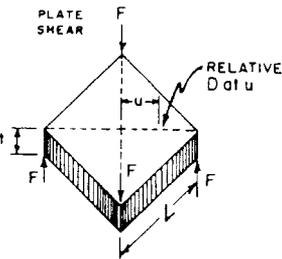
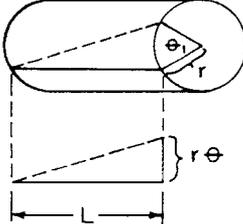
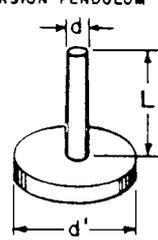
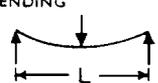
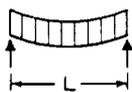
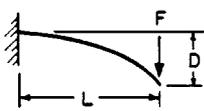
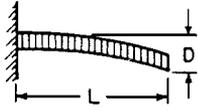
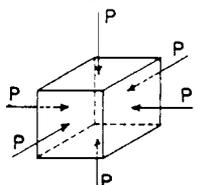
Type of Test	Parameter and Calculating Formula
<p>SHEAR PUNCH SHEAR</p> 	<p>Punch shear</p> $S = \frac{F}{\pi dt_p}$
<p>DOUBLE SHEAR</p> 	<p>Double shear</p> $S = \frac{F}{2A}$
<p>PARALLEL SHEAR</p> 	<p>Parallel shear</p> $S_s = F/2A; \epsilon_s = \tan \theta; G = S_s/\epsilon_s;$ $E = 2G(1 + \mu); 1/E = 1/3G + 1/9K$
<p>PLATE SHEAR</p> 	<p>Plate shear</p> $S_{s_{max}} = \pm \frac{3F}{t_p^2}; \epsilon_s = \pm \frac{3F}{Gt_p^2}$ $G = \frac{3Fu^2}{2Dt_p^3}; 50 > L/R > 25$ <p>$R =$ radius of curvature at u</p>
<p>TORSION TORSION BAR</p> 	<p>Torsion</p> $S_s = \frac{2T}{\pi r^3};$ $\epsilon_s = \frac{r\theta}{L};$ $G = \frac{2TL}{\pi r^4\theta}$ $\theta_1 = \theta$

Table 3.A2a. (Continued)

Type of Test	Parameter and Calculating Formula
<p>TORSION PENDULUM</p> 	<p>Torsion pendulum</p> $G = \frac{16\pi f^2 W(d')^2 L}{g d^4}$ <p>$W =$ weight of disk (N)</p> <p>$g = 9.81 \text{ m}\cdot\text{s}^{-2}$</p>
<p>BENDING</p> 	<p>Simple bending</p> $E = \frac{FL^3}{48DI}$
	<p>Simple bending (uniformly distributed load)</p> $E = \frac{5wL^4}{384DI}$
	<p>Cantilever</p> $E = \frac{FL^3}{3DI}$
	<p>Cantilever (uniformly distributed load)</p> $E = \frac{wL^4}{8DI}$
<p>BULK COMPRESSION</p> 	<p>Bulk compression</p> $K = -\frac{\Delta p}{\Delta v/v}; B = 1/K$ $1/E = 1/3G + 1/9K$

(Cont.)

Table 3.A2a. (Continued)

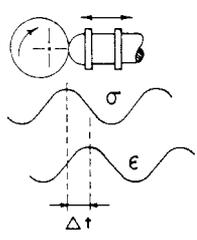
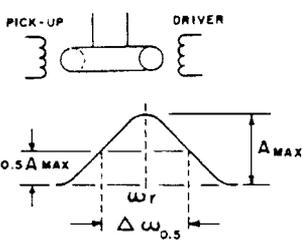
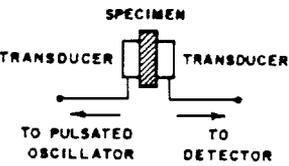
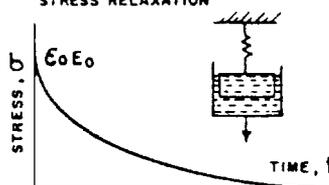
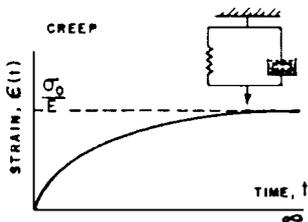
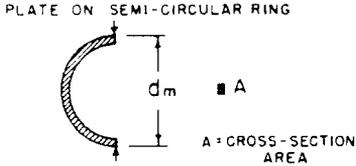
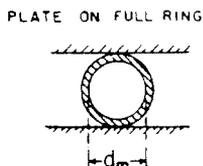
Type of Test	Parameter and Calculating Formula
<p>DYNAMIC LOADING</p> <p>DIRECT STRESS AND STRAIN</p> 	<p>Dynamic loading</p> $ E^* = F_{max}/\epsilon_{max}; \delta = w \Delta t$ $E' = E^* \cos \delta; E'' = E^* \sin \delta$
<p>RESONANCE</p> 	<p>Resonance</p> $\tan \delta = \frac{\Delta \omega_{0.5}}{\omega_r \sqrt{3}};$ $E = \frac{38.3 \rho L^4 f_r^2}{d^2}$
<p>PULSE TECHNIQUE</p> 	<p>Pulse technique</p> $E = K \rho V^2$
<p>TRANSIENT LOADING</p> <p>STRESS RELAXATION</p> 	<p>Transient loading</p> $\sigma(t) = \epsilon_0 (E_{d1} e^{-t/T_1} + E_{d2} e^{-t/T_2} + \dots + E_{dn} e^{-t/T_n} + E_e)$

Table 3.A2. (Continued)

Type of Test	Parameter and Calculating Formula
	Creep
	$\varepsilon(t) = \sigma_0(1/E_0 + 1/E_{r1}(1 - e^{-t/T_1}) + 1/E_{r2}(1 - e^{-t/T_2}) + \dots + 1/E_{rn}(1 - e^{-t/T_n}) + t/\eta_v)$
<p>PLATE ON SEMI-CIRCULAR RING</p> 	<p>Plate on semicircular ring</p> $D = \frac{0.0981 F d^3 m}{E I}$ $\sigma_{\text{tension}} = \frac{F d m C}{2 I} - \frac{F}{A}$ $\sigma_{\text{compression}} = \frac{F d m C}{2 I} + \frac{F}{A}$
<p>PLATE ON FULL RING</p> 	<p>Plate on full ring</p> $D = \frac{0.0187 F d^3 m}{E I}$ $\sigma_{\text{tension}} = \frac{0.159 F d m C}{I}$ $\sigma_{\text{compression}} = \frac{0.159 F d m C}{I}$

Source [1]: Mohsenin, N. N. 1986. *Physical Properties of Plant and Animal Materials*. Amsterdam: Gordon and Breach.

List of Symbols

- A cross-section area (m²)
- a radius of the circle of contact or radius of the die (m)
- B compressibility (Pa⁻¹)
- b, h sides of a rectangular bar (m)
- C distance from the neutral axis of the cross-section to the extreme fiber, (m)
- D deformation at single contact (m)

d	diameter of spherical indenter or rod (m)
d_1, d_2	diameters of sphere 1 and sphere 2 (m)
E	Young's modulus (Pa) (note: equivalent to Y in Section 3.3)
E^*	complex dynamic modulus (Pa)
E'	storage modulus (Pa)
E''	loss modulus (Pa)
E_d	decay modulus
E_e	equilibrium modulus
E_r	retarded modulus
e	base of Naperian log ($e = 2.72$)
F	force (N)
f	frequency (cps)
G	shear modulus (Pa)
I	moment of inertia (m^4)
I	$bh^3/12$ (rectangular bar) (m^4)
I	$\frac{\pi r^4}{4}$ round bar (m^4)
K	bulk modulus (Pa)
K	constant in $K\rho v^2$
L	length (m)
m, n, k	constants for analysis of convex bodies (see [1])
Q	$\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}$ in point loading (Pa^{-1})
R_1, R'_1	radii of convex body (m)
R_2, R'_2	radii of rigid loading devices (m)
r	distance from centre of the area over which the die is acting or radius of solid bar (m)
S	shear stress (Pa)
S_{max}	maximum normal stress (Pa)
T	torque (Nm)
T_i	time constant = n/E
t_p	thickness of plate (m)
t	time (s)
V	compressional pulse velocity (m/s)
v	volume (m^3)
w	weight per unit length (N/m)
ΔL	change in length (m)
Δp	change in pressure (Pa)
Δv	change in volume (m^3)
δ	phase angle (radians)
ε	strain (m/m)
ε_{max}	peak strain (m/m)
ε_0	strain at time 0
$\varepsilon(t)$	strain at any time (t)

η_v	viscosity
θ	angle of twist (radians)
$\tan \theta$	shear strain
ϕ	Angle between normal planes containing principle curvatures R_1 etc.
μ	Poisson's ratio
ρ	mass density (Kgm^{-3})
σ	stress (Pa)
σ_{\max}	peak stress (Pa)
σ_0	stress at time 0
$\sigma(t)$	stress at any time (t)
σ_{tension}	maximum tensile stress in the extreme fibre of the ring or semi-circular ring at failure (Pa)
$\sigma_{\text{compression}}$	Maximum compressive stress in the extreme fibre of the ring or semi-circular ring at failure, (Pa)
ω	angular frequency (radians/sec)
ω_r	resonance frequency (radians/sec)

Calculation for $\cos T_k$

$$\cos T_k = \frac{[(1/R_1 - 1/R'_1)^2 + (1/R_2 - 1/R'_2)^2 + 2(1/R_1 - 1/R'_1)(1/R_2 - 1/R'_2) \cos 2\Phi]^{1/2}}{(1/R_1 + 1/R'_1 + 1/R_2 + 1/R'_2)} \quad (1)$$

where ϕ is the angle between normal planes containing principle curvatures R_1 etc.

Table 3.A2b. Values of m , n , and k corresponding to values of T from Eqn. (1)

$\text{Cos } T_k$	m	n	k	$\text{Cos } T$	m	n	k
0	1.000	1.000	1.351	0.932	3.631	0.423	0.839
0.040	1.027	0.974	1.351	0.952	4.187	0.393	0.772
0.100	1.070	0.936	1.348	0.968	4.94	0.361	0.699
0.200	1.150	0.878	1.339	0.980	5.94	0.328	0.621
0.300	1.242	0.822	1.323	0.984	6.47	0.314	0.586
0.400	1.351	0.769	1.300	0.988	7.25	0.298	0.545
0.500	1.484	0.717	1.267	0.991	8.10	0.281	0.504
0.600	1.660	0.664	1.222	0.993	8.90	0.268	0.472
0.700	1.905	0.608	1.160	0.995	10.14	0.251	0.432
0.800	2.292	0.545	1.070	0.997	12.26	0.228	0.376
0.855	2.638	0.502	0.998	0.999	18.49	0.185	0.278
0.905	3.160	0.455	0.908				

Table 3-A3a. Normal conditions for long-term storage of fresh fruits and vegetables

Common Name	Scientific Name	Storage Temperature (°C)	Relative Humidity (%)	Highest Freezing Temperature (°C)	Ethylene Production Rate ^a	Ethylene Sensitivity ^b	Approximate Shelf life
Acerola, Barbados cherry	<i>Malpighia glabra</i>	0	85–90	-1.4	L	M	6–8 wk
African horned melon, kiwano	<i>Cucumis africanus</i>	13–15	90				6 mo
Amaranth, pigweed	<i>Amaranthus</i> spp.	0–2	95–100		VL	M	10–14 d
Anise, fennel	<i>Foeniculum vulgare</i>	0–2	90–95	-1.1			2–3 wk
Apple	<i>Malus pumila</i>				VH	H	3–6 mo
Not sensitive to chilling		-1.1	90–95	-1.5	VH	H	1–2 mo
Sensitive to chilling (Yellow Newtown, Grimes, Golden, McIntosh)		4	90–95	-1.5			
Apricot	<i>Prunus armeniaca</i>	-0.5–0	90–95	-1.1	M	H	1–3 wk
Artichoke							
Globe	<i>Cynara scolymus</i>	0	95–100	-1.2	VL	L	2–3 wk
Chinese	<i>Stachys affinis</i>	0	90–95		VL	VL	1–2 wk
Jerusalem	<i>Helianthus tuberosus</i>	-0.5–0	90–95	-2.5	VL	L	4 mo
Arugula	<i>Erca vesicaria</i> var. <i>sativa</i>	0	95–100		VL	H	7–10 d
Asian pear, nashi	<i>Pyrus serotina</i> , <i>P. pyrifolia</i>	1	90–95	-1.6	H	H	4–6 mo
Asparagus, green, and white	<i>Asparagus officinalis</i>	2.5	95–100	-0.6	VL	M	2–3 wk
Atemoya	<i>Annona squamosa</i> x <i>A. cherimola</i>	13	85–90		H	H	4–6 wk
Avocado	<i>Persea americana</i>						
cv. Fuerte, Hass		3–7	85–90	-1.6	H	H	2–4 wk
cv. Fuchs, Pollock		13	85–90	-0.9	H	H	2 wk
cv. Lula, Booth		4	90–95	-0.9	H	H	4–8 wk
Babaco, Mt. papaya	<i>Carica candamarcensis</i>	7	85–90				1–3 wk
Banana	<i>Musa paradisiiaca</i> var. <i>sapientum</i>	13–15	90–95	-0.8	M	H	1–4 wk
Beans							
Snap, wax, green	<i>Phaseolus vulgaris</i>	4–7	95	-0.7	L	M	7–10 d
Faba, broad	<i>Vicia faba</i>	0	90–95				1–2 wk

Lima	<i>Phaseolus lunatus</i>	5-6	95	-0.6	L	M	5-7 d
Winged	<i>Sophocarpus tetragonolobus</i>	10	90		L	M	4 wk
Long, yard-long	<i>Vigna sesquipedalis</i>	4-7	90-95		L	M	7-10 d
Beet							
Bunched	<i>Beta vulgaris</i>	0	98-100	-0.4	VL	L	10-14 days
Topped		0	98-100	-0.9	VL	L	4 mo
Berries							
Blackberry	<i>Rubus</i> spp.	-0.5-0	90-95	-0.8	L	L	3-6 d
Blueberry	<i>Vaccinium corymbosum</i>	-0.5-0	90-95	-1.3	L	L	10-18 d
Cranberry	<i>Vaccinium macrocarpon</i>	2-5	90-95	-0.9	L	L	8-16 wk
Dewberry	<i>Rubus</i> spp.	-0.5-0	90-95	-1.3	L	L	2-3 d
Elderberry	<i>Rubus</i> spp.	-0.5-0	90-95	-1.1	L	L	5-14 d
Loganberry	<i>Rubus</i> spp.	-0.5-0	90-95	-1.7	L	L	2-3 d
Raspberry	<i>Rubus idaeus</i>	-0.5-0	90-95	-0.9	L	L	3-6 d
Strawberry	<i>Fragaria</i> spp.	0	90-95	-0.8	L	L	7-10 d
Bittermelon, bitter gourd	<i>Momordica charantia</i>	10-12	85-90		L	M	2-3 wk
Black salsify, scorzonera	<i>Scorzonera hispanica</i>	0-1	95-98		VL	L	6 mo
Bok choy	<i>Brassica chinensis</i>	0	95-100		VL	H	3 wk
Breadfruit	<i>Artocarpus altilis</i>	13-15	85-90		VL	H	2-6 wk
Broccoli	<i>B. oleracea</i> var. <i>italica</i>	0	95-100	-0.6	VL	H	10-14 d
Brussel sprouts	<i>B. oleracea</i> var. <i>gemmifera</i>	0	95-100	-0.8	VL	H	3-5 wk
Cabbage							
Chinese, Napa	<i>Brassica campestris</i> var. <i>pekinensis</i>	0	95-100	-0.9	VL	H	2-3 mo
Common							
Early crop	<i>B. oleracea</i> var. <i>Capitata</i>	0	98-100	-0.9	VL	H	3-6 wk
Late crop	<i>B. oleracea</i> var. <i>Capitata</i>	0	95-100	-0.9	VL	H	5-6 mo
Cactus leaves, nopalitos	<i>Opuntia</i> spp.	5-10	90-95		VL	M	2-3 wk
Cactus fruit, prickly pear fruit	<i>Opuntia</i> spp.	5	85-90	-1.8	VL	M	3 wk
Carambola, starfruit	<i>Averrhoa carambola</i>	9-10	85-90	-1.2	VL	M	3-4 wk
Carrots	<i>Daucus carota</i>						
Topped		0	98-100	-1.4	VL	H	6-8 mo
Bunched, immature		0	98-100	-1.4	VL	H	10-14 d

(Cont.)

Table 3.A3a. (Continued)

Common Name	Scientific Name	Storage Temperature (°C)	Relative Humidity (%)	Highest Freezing Temperature (°C)	Ethylene Production Rate ^a	Ethylene Sensitivity ^b	Approximate Shelf life
Cashew apple	<i>Anacardium occidentale</i>	0-2	85-90				5 wk
Cassava, yucca, manioc	<i>Manihot esculenta</i>	0-5	85-90		VL	L	1-2 mo
Cauliflower	<i>B. oleracea</i> var. <i>botrytis</i>	0	95-98	-0.8	VL	H	3-4 wk
Celery	<i>Apium graveolens</i> var. <i>Rapaceum</i>	0	98-100	-0.9	VL	L	6-8 mo
Celery	<i>Apium graveolens</i> var. <i>dulce</i>	0	98-100	-0.5	VL	M	1-2 mo
Chard	<i>Beta vulgaris</i> var. <i>cicla</i>	0	95-100		VL	H	10-14 d
Chayote	<i>Sechium edule</i>	7	85-90				4-6 wk
Cherimoya, custard apple	<i>Annona cherimola</i>	13	90-95	-2.2	H	H	2-4 wk
Cherries							
Sour	<i>Prunus cerasus</i>	0	90-95	-1.7			3-7 d
Sweet	<i>Prunus avium</i>	-1-0	90-95	-2.1			2-3 wk
Chinese broccoli, gailan	<i>Brassica alboglabra</i>	0	95-100		VL	H	10-14 d
Chives	<i>Allium schoenoprasum</i>	0	95-100		VL	H	2-3 wk
Cilantro, Chinese parsley	<i>Coriandrum sativum</i>	0-2	95-100		VL	H	2 wk
Citrus							
Calamondin orange	<i>Citrus reticulata</i> x <i>Fortunella</i> spp.	9-10	90	-2.0			2 wk
Grapefruit	<i>Citrus paradisi</i>						
California, Arizona, dry areas		14-15	85-90	-1.1	VL	M	6-8 wk
FL, humid areas		10-15	85-90	-1.1	VL	M	6-8 wk
Kumquat	<i>Fortunella japonica</i>	4	90-95				2-4 wk
Lemon	<i>Citrus limon</i>	10-13	85-90	-1.4			1-6 mo
Lime, Mexican, Tahiti, or Persian	<i>Citrus aurantifolia</i> , <i>C. latifolia</i>	9-10	85-90	-1.6			6-8 wk
Orange	<i>Citrus sinensis</i>						
CA, AZ, dry areas		3-9	85-90	-0.8	VL	M	3-8 wk
FL; humid regions		0-2	85-90	-0.8	VL	M	8-12 wk
Blood		4-7	90-95	-0.8			3-8 wk
Seville, sour		10	85-90	-0.8	L	N	12 wk

Pummelo	<i>Citrus grandis</i>	7-9	85-90	-1.6			12 wk
Tangelo, Minneola	<i>Citrus reticulata</i>	7-10	85-95	-0.9			
Tangerine, Mandarin	<i>Citrus reticulata</i>	4-7	90-95	-1.1	VL	M	2-4 wk
Coconut	<i>Cocos nucifera</i>	0-2	89-85	-0.9			1-2 mo
Collards, kale	<i>B. oleracea</i> var. <i>Acephala</i>	0	95-100	-0.5	VL	H	10-14 d
Corn, sweet and baby	<i>Zea mays</i>	0	95-98	-0.6	VL	L	5-8 d
Cucumber	<i>Cucumis sativus</i>	10-12	85-90	-0.5	L	H	10-14 d
Pickling		4	95-100		L	H	7 d
Currants	<i>Ribes sativum</i> ,	-0.5-0	90-95	-1.0	L	L	1-4 wk
	<i>R. nigrum</i> , <i>R. rubrum</i>						
Daikon, Oriental radish	<i>Raphanus sativus</i>	0-1	95-100		VL	L	4 mo
Date	<i>Phoenix dactylifera</i>	-18-0	75	-15.7	VL	L	6-12 mo
Durian	<i>Durio zibethinus</i>	4-6	85-90				6-8 wk
Eggplant	<i>Solanum melongena</i>	10-12	90-95	-0.8	L	M	1-2 wk
Endive		0	95-100	-0.1	VL	M	2-4 wk
escarole	<i>Cichorium endivia</i>						
belgian endive, witloof	<i>Cichorium intybus</i>	2-3	95-98		VL	M	2-4 wk
chicory							
Feijoa, pineapple guava	<i>Feijoa sellowiana</i>	5-10	90		M	L	2-3 wk
Fig, fresh	<i>Ficus carica</i>	-0.5-0	85-90	-2.4	M	L	7-10 d
Garlic	<i>Allium sativum</i>	0	65-70	-0.8	VL	L	6-7 mo
Ginger	<i>Zingiber officinale</i>	13	65		VL	L	6 mo
Gooseberry	<i>Ribes grossularia</i>	-0.5-0	90-95	-1.1	L	L	3-4 wk
Grape	<i>Vitis vinifera</i>	-0.5-0	90-95	-2.7	VL	L	2-8 wk
American	<i>Vitis labrusca</i>	-1-0.5	90-95	-1.4	VL	L	1-6 mo
Guava	<i>Psidium guajava</i>	5-10	90		L	M	2-3 wk
Herbs, fresh culinary							
Basil	<i>Ocimum basilicum</i>	10	90		VL	H	7 d
Chives	<i>Allium schoenorasum</i>	0	95-100	-0.9	L	M	
Dill	<i>Anethum graveolens</i>	0	95-100	-0.7	VL	H	1-2 wk
Epazote	<i>Chenopodium</i>	0-5	90-95		VL	M	1-2 wk
	<i>ambrosioides</i>						
Mint	<i>Mentha</i> spp.	0	95-100		VL	H	2-3 wk
Oregano	<i>Origanum vulgare</i>	0-5	90-95		VL	M	1-2 wk
Parsley	<i>Petroselinum crispum</i>	0	95-100	-1.1	VL	H	1-2 mo

(Cont.)

Table 3.A3a. (Continued)

Common Name	Scientific Name	Storage Temperature (°C)	Relative Humidity (%)	Highest Freezing Temperature (°C)	Ethylene Production Rate ^a	Ethylene Sensitivity ^b	Approximate Shelf life
Perilla, shiso	<i>Perilla frutescens</i>	10	95		VL	M	7 d
Sage	<i>Salvia officinalis</i>	0	90–95				2–3 wk
Thyme	<i>Thymus vulgaris</i>	0	90–95				2–3 wk
Horseradish	<i>Armoracia rusticana</i>	-1–0	98–100	-1.8	VL	L	10–12 mo
Jaboticaba	<i>Myrciaria cauliflora</i> (<i>Eugenia cauliflora</i>)	13–15	90–95				2–3 d
Jackfruit	<i>Artocarpus heterophyllus</i>	13	85–90		M	M	2–6 wk
Jicama, yambean	<i>Pachyrhizus erosus</i>	13–18	85–90		VL	L	1–2 mo
Jujube, Chinese date	<i>Ziziphus jujuba</i>	2.5–10	85–90	-1.6	L	M	1 mo
Kale	<i>B. oleracea</i> var. <i>acephala</i>	0	95–100	-0.5	VL	M	
Kiwifruit,	<i>Actinidia chinensis</i>	0	90–95	-0.9	L	H	3–5 mo
Chinese gooseberry							
Kohlrabi	<i>B. oleracea</i> var. <i>gongylodes</i>	0	98–100	-1.0	VL	L	2–3 mo
Langsat, lanzone	<i>Aglaia</i> spp., <i>Lansium</i> spp.	11–14	85–90				2 wk
Leafy greens							
Cool-season	Various genera	0	95–100	-0.6	VL	H	10–14 d
Warm-season	Various genera	7–10	95–100	-0.6	VL	H	5–7 d
Leek	<i>Allium porrum</i>	0	95–100	-0.7	VL	M	2 mo
Lettuce	<i>Lactuca sativa</i>	0	98–100	-0.2	VL	H	2–3 wk
Longan	<i>Dimocarpus longan</i> (<i>Euphoria longan</i>)	1–2	90–95	-2.4			3–5 wk
Loquat	<i>Eriobotrya japonica</i>	0	90	-1.9			3 wk
Luffa, Chinese okra	<i>Luffa</i> spp.	10–12	90–95		L	M	1–2 wk
Lychee, litchi	<i>Litchi chinensis</i>	1–2	90–95		M	M	3–5 wk
Malanga, tania, new cocoyam	<i>Xanthosoma sagittifolium</i>	7	70–80		VL	L	3 mo
Mango	<i>Mangifera indica</i>	13	85–90	-1.4	M	M	2–3 wk
Mangosteen	<i>Garcinia mangostana</i>	13	85–90		M	H	2–4 wk
Melons							
Cantaloupes and other netted melons	<i>Cucurbita melo</i> var. <i>reticulatus</i>	2–5	95	-1.2	H	M	2–3 wk

Casaba	<i>Cucurbita melo</i>	7-10	85-90	-1.0	L	L	3-4 wk
Grenshaw	<i>Cucurbita melo</i>	7-10	85-90	-1.1	M	M	2-3 wk
Honeydew, orange-flesh	<i>Cucurbita melo</i>	5-10	85-90	-1.1	M	M	3-4 wk
Persian	<i>Cucurbita melo</i>	7-10	85-90	-0.8	M	M	2-3 wk
Mushrooms	<i>Agaricus</i> , other genera	0	90	-0.9	VL	VL	7-14 d
Mustard greens	<i>Brassica juncea</i>	0	90-95		VL	VL	7-14 d
Nectarine	<i>Prunus persica</i>	-0.5-0	90-95	-0.9	M	M	2-4 wk
Okra	<i>Abelmoschus esculentus</i>	7-10	90-95	-1.8	L	M	7-10 d
Olives, fresh	<i>Olea europea</i>	5-10	85-90	-1.4	L	M	4-6 wk
Onions	<i>Allium cepa</i>						
Mature bulbs, dry		0	65-70	-0.8	VL	L	1-8 mo
Green onions		0	95-100	-0.9	L	H	3 wk
Papaya	<i>Carica papaya</i>	7-13	85-90				1-3 wk
Parsnips	<i>Pastinaca sativa</i>	0	95-100	-0.9	VL	H	4-6 mo
Passionfruit	<i>Passiflora</i> spp.	10	85-90		VH	M	3-4 wk
Peach	<i>Prunus persica</i>	-0.5-0	90-95	-0.9	H	H	2-4 wk
Pear, American	<i>Pyrus communis</i>	-1.5-0.5	90-95	-1.7	H	H	2-7 mo
Peas in pods	<i>Pisum sativum</i>	0-1	90-98	-0.6	VL	M	1-2 wk
Snow, snap, and sugar peas							
Southern peas, cowpeas	<i>Vigna sinensis</i>	4-5	95				6-8 d
	(<i>V. unguiculata</i>)						
Pepino, melon pear	<i>Solanum muricatum</i>	5-10	95		L	M	4 wk
Peppers							
Bell Pepper, paprika	<i>Capsicum annuum</i>	7-10	95-98	-0.7	L	L	2-3 wk
Hot peppers, chiles	<i>Capsicum annuum</i> , C. <i>frutescens</i>	5-10	85-95	-0.7	L	M	2-3 wk
Persimmon, kaki	<i>Dispyros kaki</i>						
Fuyu		10	90-95	-2.2	L	H	1-3 mo
Hachiya		5	90-95	-2.2	L	H	2-3 mo
Pineapple	<i>Ananas comosus</i>	7-13	85-90	-1.1	L	L	2-4 wk
Plantain	<i>Musa paradisiaca</i> var. <i>paradisiaca</i>	13-15	90-95	-0.8	L	H	1-5 wk
Plums and prunes	<i>Prunus domestica</i>	-0.5-0	90-95	-0.8	M	H	2-5 wk
Pomegranate	<i>Punica granatum</i>	5	90-95	-3.0			2-3 mo

(Cont.)

Table 3.A3a. (Continued)

Common Name	Scientific Name	Storage Temperature (°C)	Relative Humidity (%)	Highest Freezing Temperature (°C)	Ethylene Production Rate ^a	Ethylene Sensitivity ^b	Approximate Shelf life
Porato	<i>Solanum tuberosum</i>	10-15	90-95	-0.8	VL	M	10-14 d
Early crop		4-12	95-98	-0.8	VL	M	5-10 mo
Late crop		12-15	50-70	-0.8	L	M	2-3 mo
Pumpkin	<i>Cucurbita maxima</i>	-0.5-0	90	-2.0	L	H	2-3 mo
Quince	<i>Cydonia oblonga</i>	0-1	95-100	-0.7	VL	L	3-4 wk
Raddichio	<i>Cichorium intybus</i>	0	95-100	-0.9	H	H	1-2 mo
Radish	<i>Raphanus sativus</i>	12	90-95	-1.1	VL	L	1-3 wk
Rambutan	<i>Nephelium lappaceum</i>	0	95-100	-0.9	VL	L	2-4 wk
Rhubarb	<i>Rheum rhabarbaricum</i>	0	98-100	-1.1	VL	L	4-6 mo
Rutabaga	<i>B. napus</i> var. <i>Napobrassica</i>	0	95-98	-1.1	VL	L	2-4 mo
Salsify, vegetable oyster	<i>Trapaogon porrifolius</i>	3	90	-1.2			3 wk
Sapotes	<i>Chrysophyllum cainito</i>	13-15	85-90	-1.8			3 wk
Caimito, star apple	<i>Pouteria campechiana</i>	13-15	85-90	-2.3			2-3 wk
Canistel, eggfruit	<i>Diospyros ebenaster</i>	20	85-90	-2.0			2-3 wk
Black sapote	<i>Casimiroa edulis</i>	13-15	90-95		H	H	2-3 wk
White sapote	<i>Calocarpum mammosum</i>	15-20	85-90		H	H	2 wk
Mamey sapote	<i>Achras sapota</i>	0-2.5	65-70	-0.7	L	L	
Sapodilla, chicosapote	<i>Allium cepa</i> var. <i>ascalonicum</i>	13	85-90	-0.3	VL	H	1-2 wk
Shallots	<i>Ammona muricata</i>	0	95-100				10-14 d
Soursop	<i>Spinacia oleracea</i>	13	85-90				1-2 wk
Spinach	<i>Spondias</i> spp.	0	95-100				5-9 d
Spondias: mombin, wi apple, jobo, hogplum	Various genera	0	95-100				7 d
Sprouts from seeds	<i>Medicago sativa</i>	0	95-100				7-9 d
Alfalfa	<i>Phaseolus</i> spp.	0	95-100				5-7
Bean	<i>Raphanus</i> spp.	0	95-100				
Radish							

Table 3.A3b. Conditions for long-term storage of fresh fruits and vegetables

Common Name	Scientific Name	Observations and Beneficial Controlled Atmosphere (CA) Conditions
Apple	<i>Malus pumila</i>	2%–3%O ₂ , 1%–2%CO ₂
Apricot	<i>Prunus armeniaca</i>	2%–3%O ₂ , 2%–3%CO ₂
Artichoke globe	<i>Cynara scolymus</i>	2%–3%O ₂ , 3%–5%CO ₂
Asparagus: green, white	<i>Asparagus officinalis</i>	5%–12%CO ₂ in air
Atemoya	<i>Annona squamosa</i> x, <i>A. cherimola</i>	3%–5%O ₂ , 5%–10%CO ₂
Avocado: fuerte, hass	<i>Persea americana</i>	2%–5%O ₂ , 3%–10%CO ₂
Banana	<i>Musa paradisiaca</i> var. <i>sapientum</i>	2%–5%O ₂ , 2%–5%CO ₂
Beans: snap, wax, green	<i>Phaseolus vulgaris</i>	2%–3%O ₂ , 4%–7%CO ₂
Berries		
Blackberry	<i>Rubus</i> spp.	5%–10%O ₂ , 15%–20%CO ₂
Blueberry	<i>Vaccinium corymbosum</i>	2%–5%O ₂ , 12%–20%CO ₂
Cranberry	<i>Vaccinium macrocarpon</i>	1%–2%O ₂ , 0%–5%CO ₂
Raspberry	<i>Rubus idaeus</i>	5%–10%O ₂ , 15%–20%CO ₂
Strawberry	<i>Fragaria</i> spp.	5%–10%O ₂ , 15%–20%CO ₂
Bittermelon, bitter gourd	<i>Momordica charantia</i>	2%–3%O ₂ , 5%CO ₂
Broccoli	<i>B. oleracea</i> var. <i>italica</i>	1%–2%O ₂ , 5%–10%CO ₂
Brussel sprouts	<i>B. oleracea</i> var. <i>gemnifera</i>	1%–2%O ₂ , 5%–7%CO ₂
Cabbage		
Chinese, Napa	<i>Brassica campestris</i> var. <i>pekinensis</i>	1%–2%O ₂ , 0%–5%CO ₂
Common, late crop	<i>B. oleracea</i> var. <i>capitata</i>	3%–5%O ₂ , 3%–7%CO ₂
Carrots	<i>Daucus carota</i>	No CA benefit
Topped		
Bunched, immature		Ethylene causes bitterness
Cassava, yucca, manioc	<i>Manihot esculenta</i>	No CA benefit
Cauliflower	<i>B. oleracea</i> var. <i>botrytis</i>	2%–5%O ₂ , 2%–5%CO ₂
Celeriac	<i>Apium graveolens</i> var. <i>rapaceum</i>	2%–4%O ₂ , 2%–3%CO ₂
Celery	<i>Apium graveolens</i> var. <i>Dulce</i>	1%–4%O ₂ , 3%–5%CO ₂
Cherimoya, custard apple	<i>Annona cherimola</i>	3%–5%O ₂ , 5%–10%CO ₂
Cherries		3%–10%O ₂ , 10%–12%CO ₂
Sour	<i>Prunus cerasus</i>	
Sweet	<i>Prunus avium</i>	10%–20%O ₂ , 20%–25%CO ₂
Citrus		
Grapefruit	<i>Citrus paradisi</i>	3%–10%O ₂ , 5%–10%CO ₂
Lemon	<i>Citrus limon</i>	5%–10%O ₂ , 0%–10%CO ₂ store at 0–5°C for <1 mo
Lime: Mexican, Tahiti, or Persian	<i>Citrus aurantifolia</i> , <i>C. latifolia</i>	5%–10%O ₂ , 0%–10%CO ₂
Orange	<i>Citrus sinensis</i>	5%–10%O ₂ , 0%–5%CO ₂
Corn, sweet and baby	<i>Zea mays</i>	2%–4%O ₂ , 5%–10%CO ₂
Cucumber	<i>Cucumis sativus</i>	
Pickling		3%–5%O ₂ , 3%–5%CO ₂
Durian	<i>Durio zibethinus</i>	3%–5%O ₂ , 5%–15%CO ₂
Eggplant	<i>Solanum melongena</i>	3%–5%O ₂ , 0%CO ₂
Endive, Belgian; witloof chicory	<i>Cichorium intybus</i>	Light causes greening; 3%–4%O ₂ , 4%–5%CO ₂

Table 3.A3b. (Continued)

Common Name	Scientific Name	Observations and Beneficial Controlled Atmosphere (CA) Conditions
Fig, fresh	<i>Ficus carica</i>	5%–10%O ₂ , 15%–20%CO ₂
Garlic	<i>Allium sativum</i>	0.5%O ₂ , 5%–10%CO ₂
Ginger	<i>Zingiber officinale</i>	No CA benefit
Grape	<i>Vitis vinifera</i>	2%–5%O ₂ , 1%–3%CO ₂ ; to 4 wk, 5%–10%O ₂ , 10%–15%CO ₂
Herbs, fresh culinary		5%–10%O ₂ , 5%–10%CO ₂
Kiwifruit	<i>Actinidia chinensis</i>	1%–2%O ₂ , 3%–5%CO ₂
Kohlrabi	<i>B. oleracea</i> var. <i>Gongyloides</i>	No CA benefit
Leek	<i>Allium porrum</i>	1%–2%O ₂ , 2%–5%CO ₂
Lettuce	<i>Lactuca sativa</i>	2%–5%O ₂ , 0%CO ₂
Lychee, litchi	<i>Litchi chinensis</i>	3%–5%O ₂ , 3%–5%CO ₂
Mango	<i>Mangifera indica</i>	3%–5%O ₂ , 5%–10%CO ₂
Melons		
Cantaloupes and other netted melons	<i>Cucurbita melo</i> var. <i>reticulatus</i>	3%–5%O ₂ , 10%–15%CO ₂
Casaba	<i>Cucurbita melo</i>	3%–5%O ₂ , 5%–10%CO ₂
Crenshaw	<i>Cucurbita melo</i>	3%–5%O ₂ , 5%–10%CO ₂
Honeydew, orange-flesh	<i>Cucurbita melo</i>	3%–5%O ₂ , 5%–10%CO ₂
Persian	<i>Cucurbita melo</i>	3%–5%O ₂ , 5%–10%CO ₂
Mushrooms	<i>Agaricus</i> , other genera	3%–21%O ₂ , 5%–15%CO ₂
Nectarine	<i>Prunus persica</i>	1%–2%O ₂ , 3%–5%CO ₂ ; internal breakdown 3–10°C
Okra	<i>Abelmoschus esculentus</i>	air and 4%–10%CO ₂
Olives, fresh	<i>Olea europea</i>	2%–3%O ₂ , 0%–1%CO ₂
Onions		
Mature bulbs, dry		1%–3%O ₂ , 5%–10%CO ₂
Green		2%–4%O ₂ , 10%–20%CO ₂
Papaya	<i>Carica papaya</i>	2%–5%O ₂ , 5%–8%CO ₂
Parsnips	<i>Pastinaca sativa</i>	Ethylene causes bitterness
Peach	<i>Prunus persica</i>	1%–2%O ₂ , 3%–5%CO ₂ ; internal breakdown 3–10°C
Pear, American	<i>Pyrus communis</i>	Cultivar variations; 1%–3%O ₂ , 0%–5%CO ₂
Peas in pods: snow, snap, and sugar peas	<i>Pisum sativum</i>	2%–3%O ₂ , 2%–3%CO ₂
Peppers		
Bell, paprika	<i>Capsicum annuum</i>	2%–5%O ₂ , 2%–5%CO ₂
Hot, chiles	<i>Capsicum annuum</i> , <i>C. frutescens</i>	3%–5%O ₂ , 5%–10%CO ₂
Persimmon, kaki	<i>Dispyros kaki</i>	3%–5%O ₂ , 5%–8%CO ₂
Pineapple	<i>Ananas comosus</i>	2%–5%O ₂ , 5%–10%CO ₂
Plums and prunes	<i>Prunus domestica</i>	1%–2%O ₂ , 0%–5%CO ₂
Pomegranate	<i>Punica granatum</i>	3%–5%O ₂ , 5%–10%CO ₂
Potato	<i>Solanum tuberosum</i>	No CA benefit
Radish	<i>Raphanus sativus</i>	1%–2%O ₂ , 2%–3%CO ₂

(Cont.)

Table 3.A3b. (Continued)

Common Name	Scientific Name	Observations and Beneficial Controlled Atmosphere (CA) Conditions
Rambutan	<i>Nephelium lappaceum</i>	3%–5%O ₂ , 7%–12%CO ₂
Spinach	<i>Spinacia oleracea</i>	5%–10%O ₂ , 5%–10%CO ₂
Squash		
Summer (soft rind), courgette	<i>Cucurbita pepo</i>	3%–5%O ₂ , 5%–10%CO ₂
Winter (hard rind), calabash	<i>Cucurbita moschata</i> , <i>C. maxima</i>	Large differences among varieties
Sweetsop, sugar apple, custard apple	<i>Annona squamosa</i> , <i>Annona</i> spp.	3%–5%O ₂ , 5%–10%CO ₂
Taro, cocoyam, eddoe, dasheen	<i>Colocasia esculenta</i>	No CA benefit
Tomato	<i>Lycopersicon esculentum</i>	
Mature green		3%–5%O ₂ , 2%–3%CO ₂
Firm ripe		3%–5%O ₂ , 3%–5%CO ₂
Watermelon	<i>Citrullus vulgaris</i>	No CA benefit

Adapted from Kader, A. A. 1999. Postharvest technology of agricultural crops. Publication 3311, 3rd ed. University of California, Davis.

^a Ethylene production rate: VL = very low (<0.1 μ L/kg·hr at 20°C); L = low (0.1–1.0 μ L/kg·hr); M = moderate (1.0–10.0 μ L/kg·hr); H = high (10–100 μ L/kg·hr); VH = very high (>100 μ L/kg·hr).

^b Ethylene sensitivity (detrimental effects include yellowing, softening, increased decay, loss of leaves, browning): L = low sensitivity; M = moderately sensitive; H = highly sensitive.

Sources used for compilation of data:

- Facciola, S. 1990. *Cornucopia. A Source Book of Edible Plants*, Kampong Pub., Vistal, CA;
- Hardenburg, R., A. E. Watada, C. Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. *USDA Agric. Handbook No. 66*.
- Kader, A. A. et al. 1992. *Postharvest Technology of Horticultural Crops*. University California Pub. 3311
- Kays, S. J. and J. C. Silva Dias. 1996. *Cultivated Vegetables of the World*, Exon Press, Athens, GA.
- McGregor, B. M. 1987. Manual de transporte de productos tropicales, *USDA Agric. Handbook No. 668*.
- Maersk, *Sealand and APL shipping guides. Proceedings 6th and 7th International Controlled Atmosphere Research Conferences*.
- Rubatzky, V. E. and M. Yamaguchi. 1997. *World Vegetables, Principles, Production and Nutritive Values*, 2nd ed., Chapman & Hall, N. Y.
- Whiteman, T. M. 1957. Freezing points of Fruits, Vegetables, and Florist Stocks, *USDA Mkt. Res. Rpt. No. 196*.
- Cantwell, unpublished data on specialty vegetables.

Table 3.A4. Orders of magnitude of elastic modulus and Poisson's ratio for selected solid foods

Material	Type of Test	Apparent Elastic Modulus (MPa)	Poisson's Ratio	Specific Gravity
Apple				
Whole	Plate compression	3.5–7		
Flesh	Axial compression	3.3–10	0.21–0.34	
Skin	Axial tensile	9.5–15	0.31–0.5	
Banana	Dynamic	0.8–1.2		
Beef	Axial compression	0.23–0.24		
Carrot	Bending	3–29		
Celery	Bending	9.9–31.5		
Cheese	Axial compression	0.16	0.5	
Corn grain	Axial compression	400–1150	0.32	
Gels (protein)	Axial tensile	0.0016–0.0103		
Noodles (cooked)	Axial tensile	0.06		
Pear	Plate compression	3.7–10		0.98–1.1
Peach	Plate compression	0.5–10		0.95–1.03
Potato (white)	Axial compression	3.2–4.3	0.49	1.1
Wheat grain	Axial compression	1200–5700	0.3	
Lemon				1.07
Grape				1.2–1.3
Plum				0.99–1.08
Tomato				1.0
Cherry				1.07–1.3
Blueberry				0.8–1.3
Cranberry				0.6
Coffee				1.0–1.2
Orange				0.93–0.95
Grapefruit				0.8–0.9

Source: Mohsenin, N. N. 1986. *Physical Properties of Plant and Animal Materials*. Amsterdam: Gordon and Breach.

4 Grapes, Olives, and Coffee

M. Ruiz-Altisent, Co-Editor

4.1 Wine Processing

F. Ayuga

4.1.1 Industrial Process

It is not the intention of this handbook to make an exhaustive exposition of the industrial elaboration process of wines. A more complete description can be seen in Refs. [1] and [2]. In this section, a description is made of the most important stages followed, according to the type of wine to be obtained.

Types of Wines

In first place, the clear differences of existing types of wines must be indicated. White or pink wines come from white grapes or a mixture with black grapes, but they acquire no color (white) or only a mild dye (pink) from the subsequent elaboration process. Red wines come from black grapes or a mixture of these with white, and they acquire the characteristic color from their elaboration process.

Processing Operations

In Fig. 4.1 flowcharts that summarize the basic elaboration operations are shown. It must be said that, within the two large groups into which wines have been divided, important different peculiarities may exist, according to the conscientiousness of manufacture and the existence or lack of intermediate operations intended to improve quality.

As can be appreciated, the difference between the elaboration systems is that the second makes the first fermentation from all the mass (husks, flesh, must and seeds, and part of stem). This causes coloration of the liquid because of the existing pigments in the husk of the black grape. The white- or pink-wine elaboration quickly separates the solid and the liquid phases. If the grape is white, white wine will be obtained, but if the whole is black, or if black and white mixtures arrive at the winery, pink wine is with different tonalities according to the proportion from each one and, above all, to the amount of time during which must and husks stay without being separated, once the grapes have been crushed. "Claret" wines are those that are obtained from black and white grapes and whose fermentation is made partially in the presence of the residues of the black grape.

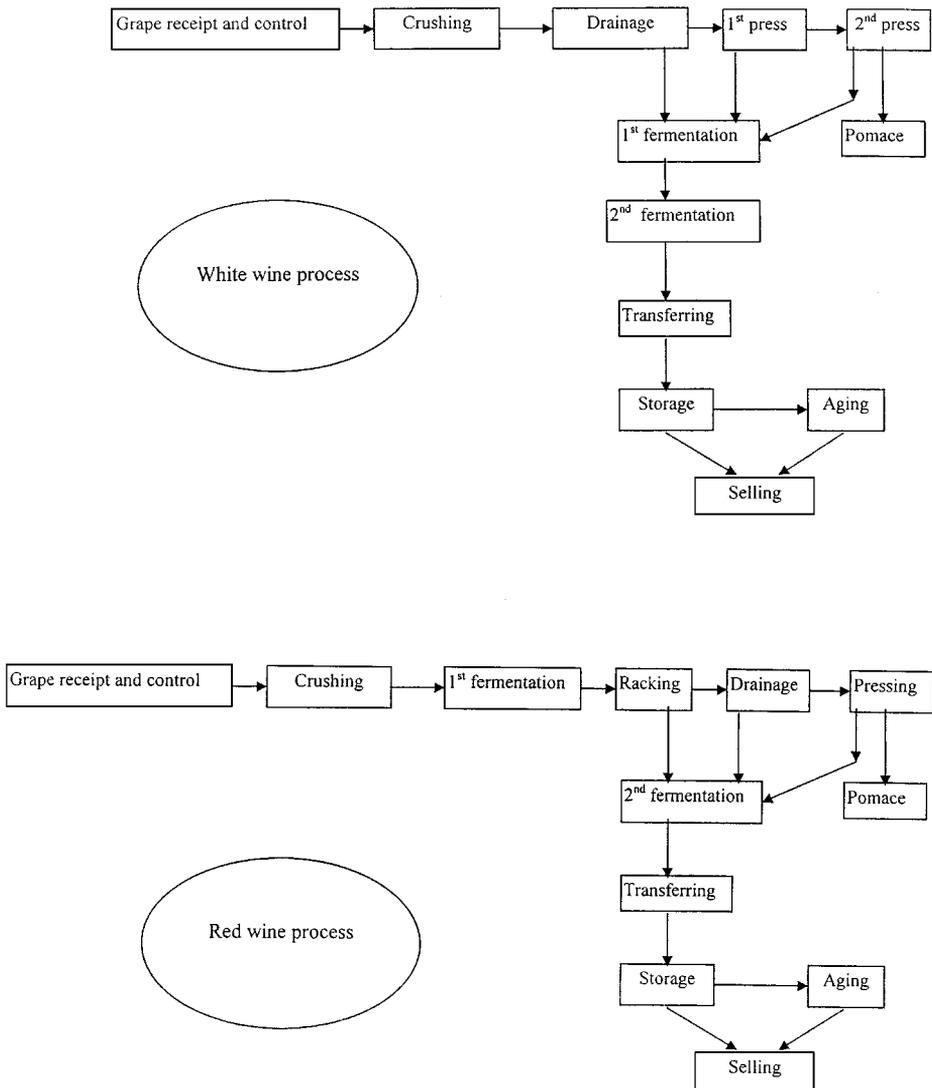


Figure 4.1. Flowcharts of white- and red-wine processes.

4.1.2 Process Description

Grape Receipt and Control

As in any other industry, at the arrival of the material loads, a control of quantity and quality must be performed. The first control is effected in a weighbridge whose advisable capacity and dimensions are 500 kN of force and a platform of 15 by 3 m. This weighbridge may seem excessive, because the vehicles that transport grapes tend to be simple agricultural tows of no more than 40- to 50-kN loads. However, such capacity

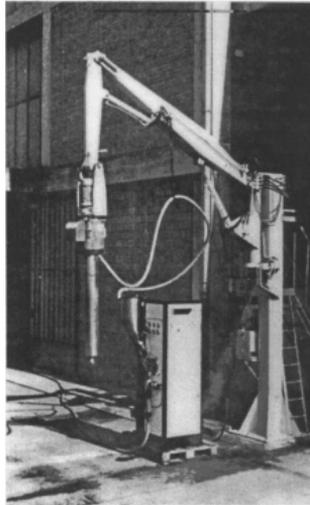


Figure 4.2. Sampling equipment.

and dimensions will permit the weighing of trucks in which the wine leaves the winery, whose dimensions are becoming larger.

As for the control of the quality, it is usual to determine the sugar content of the grape received. It is appropriate to take samples of each truck or tow. Figure 4.2 shows a model of sampling equipment, which permits obtaining samples in any part of the transportation vehicle.

Once the grape sample is obtained and crushed, the sugar content is determined by means of a densimeter or a refractometer. Automatic measurement equipment can be found in the market.

The measurement units used for sugar content are as follows: *Baumé degrees* depend on density, which is greater for higher sugar concentrations. A table relates degrees Baumé to glucose content (each degree Baumé is approximately equal to 1.75% sugar). *Probable alcohol degrees* express the percentage of alcohol that will be obtained upon transforming the must into wine. *Brix degrees* indicate the percentage of glucose in the must.

The photoelectric refractometer is able to print a label with the glucose content of the analyzed sample. This label is used to identify the shipment and allows the farmer to be paid as a function of the quantity and quality of the delivered product.

Crush

Once the operation of control is finished, the grape is poured into a large hopper, from which the processing begins. The operation of pouring can be helped by an unloading tipping platform where the tow is fixed (Fig. 4.3). A quick and comfortable emptying is secured this way. If such a platform does not exist, the unloading has to

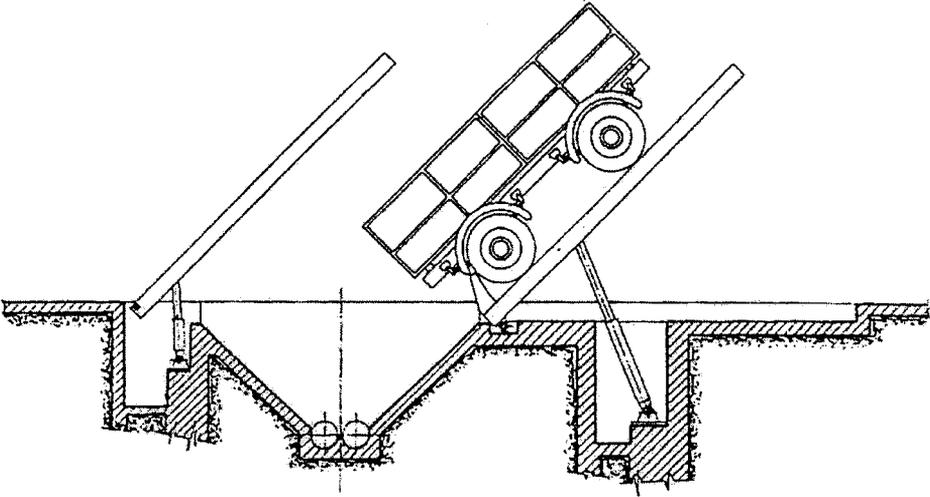


Figure 4.3. Unloading tipping platform.

be done manually, except in cases in which the transportation is made in self-dumping vehicles.

The hoppers (Fig. 4.3) are dihedral angled bins in which a conveyor formed by one or two worm screws leads the grape clusters to the crusher located at one end. This machine breaks the grapes and separates the stems in the desired proportion. A complete destemming is not advisable if the press procedure is not of the soft type (see subsequent paragraphs), as the presence of stems facilitates the subsequent pressing of the paste (Fig. 4.4).

Sometimes the use of grape harvesters leads to a complete destemming; therefore, the grape material is received in the winery without stems.

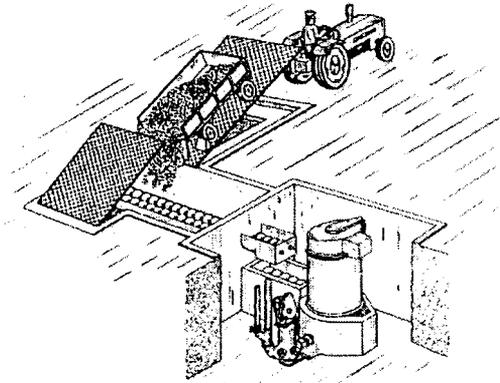


Figure 4.4. Hopper, crusher, and destemming system.



Figure 4.5. Crushing and destemming machine.

The model in Fig. 4.5 corresponds to a machine that has both a destemming unit and a crushing unit. Its revolving shaft is vertical.

Also there is the possibility of separating the destemming machine from the crushing machine. Their revolving shafts are then horizontal.

There also exist machines that perform a “soft” crushing by means of bands. The previously destemmed grapes pass along successive rollers between the bands, which apply a low pressure and brake the grapes without altering the seeds. This process improves the quality of the wine.

The mixture of broken husks, flesh, must, seeds, and a fraction of the stems falls into the base of the crushing machine, where it is captured by a vintage pump that through an adapted pipeline sends it to the press room, in the case of white-wine elaboration, or the fermentation tanks in the case of red-wine elaboration.

Drainage and Pressing

The processes of drainage and pressing are performed in the press room. Here the complete separation between solid phases and liquid phases is made.

Drainage

Drainage is accomplished in a simple machine with a bottom made of brass or punctured bronze that, in the manner of a colander, makes a first separation, obtaining on the one hand not-pressed must (50% of the total) and additionally drained paste (Fig. 4.6). To facilitate filtering, some equipment is provided with a vibrator. The movement of the paste within the drain hopper is made by gravity, the bottom being inclined, or through worms that move it from the entry end to the exit. The time of contact between must and solids can be regulated.

In the past, drainage was done in large cages of wood, within raised concrete bins. Under those bins, the pressing machines were installed. The must was filtered and passed to fermentation tanks, while the rest, held by the wood cages, fell to the presses. The

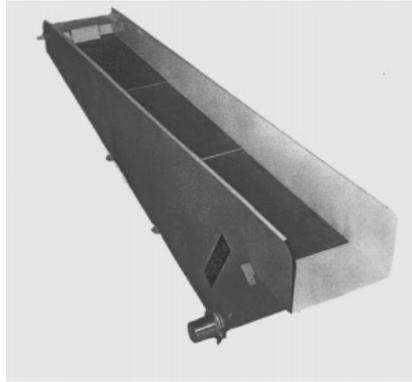


Figure 4.6. Drainage machine.

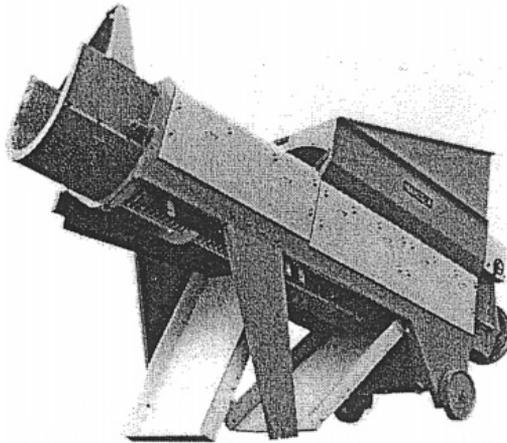


Figure 4.7. Separator press.

equipment required a considerable investment, and furthermore abundant labor was necessary for its operation.

Press

There are many different press systems, for example the continuous press system, with two series of machines with successive pressing actions. The first is called a *separator* (Fig. 4.7) and the obtained must is called “of first press” (35% of the total, approximately). The solid phase not yet exhausted passes to the proper presses (Fig. 4.8) where, submitted to great pressure, all the must that can be extracted by this procedure is extracted (15% of the total, approximately). At least two must types are separated from the presses, according to the pressure degree. The wine from the last phase of pressed must maintains, in certain grapes, some elements (named *lees*) in colloidal state and lacks transparency. It is used for distillation.

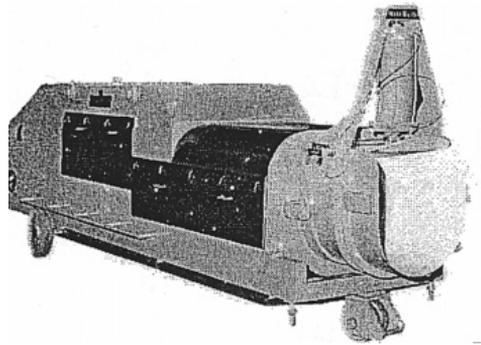


Figure 4.8. Continuous press.

The solids, which subsequently are referred to as *pomace*, remain with a little quantity of must, and they are sent to bins. These can be simple steel hoppers, raised on pillars so that a truck can pass below and collect the daily pomace production, or large bins in which pomace is stored well compacted, to get out the small amount of juice that it yet possesses and mainly to avoid rotteness. In this case, pomace bins have enough capacity for the production of a whole season and pomace sale must not be agreed on and programmed previously as in the first case; investment in storage is much greater, however. Pomace serves as raw material for the distillation industry.

A softer press system is the discontinuous horizontal press. It was used years ago and is used today in some modern wineries that take extraordinary care with elaboration. The paste is forced to a lower pressure, and because of this the musts improve their quality. The inconvenience is that much labor is needed in the pressing process, as well as that the machines have a low work capacity compared with continuous presses.

Another type of press that is used in the elaboration of quality wines and whose operation is also discontinuous is the shell press. In Fig. 4.9 appears a model that uses

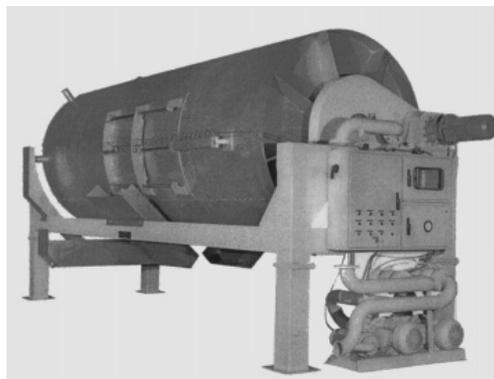


Figure 4.9. Shell press.

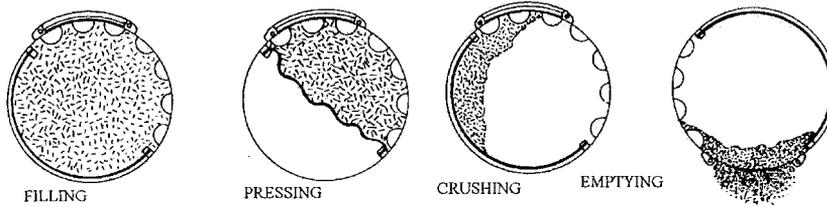


Figure 4.10. Work phases of the shell press.

water to get the pressure, and in Fig. 4.10 the work phases of that press are shown. Other similar machines use compressed air to obtain the desired pressure (pneumatic presses).

In summary, the following pressure levels applied on the paste can be established, according to the type of press:

- Shell presses, 100 to 250 kPa
- Horizontal presses, 600 to 800 kPa
- Continuous presses, 1500 kPa (approximately)

These data reveal the different treatments of the drained vintage bulk, according to the press type used, that translates to different qualities of musts and wines.

The extracted musts are led to underground bins, from where they are pumped to the fermentation tanks, or to a fining.

In Fig. 4.11 a drawing of white- and pink-wine elaboration with continuous-regime equipment is shown. For the elaboration of red wine, the section for draining and pressing also is valid, to which the pastes have been transferred from the bins in which the primary fermentation has been completed. This movement is effected with pumps of the type shown in Fig. 4.12.

Finning

The must obtained (by a white-wine elaboration process) or the must wine originated from the pressing of fermented vintage after racking (in red-wine elaboration) should be finned before continuing with the following stages, if good quality wines are desired.

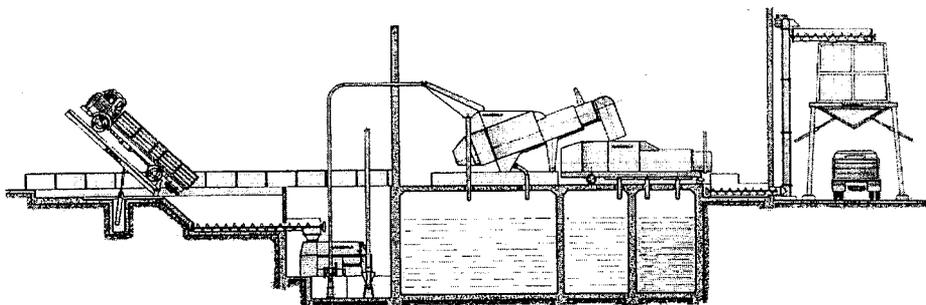


Figure 4.11. Continuous pressing of white wine.

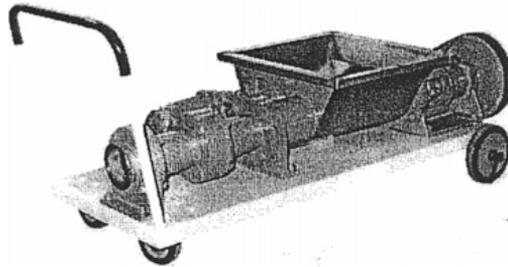


Figure 4.12. Paste pump.

Fining is procured by any of the following procedures, or by a combination of them:

- Decanting
- Centrifuging
- Filtration

Decanting

Decanting consists of maintaining the must in rest for 8 to 24 hours, in one or several tanks with previous addition of SO_2 , or at a temperature under 8°C to avoid the start of fermentation. If this system is chosen, the winery project has to be completed taking into account the need for those tanks, which should be of easy cleaning. Each decanting tank is of approximately 20 m^3 capacity. Sometimes the decanting process can be accelerated through the addition to the must of finning agents such as clarifiers, bentonite, albumin, egg white, or enzymes that decompose the membranes of the plant cells. Once the decanting process is finished, racking of the liquid takes place. Wine tanks usually have racking valves for this process.

Centrifuging

Centrifuging, consists of taking the must recently obtained from the presses and passing it through a centrifugal clarifier. Instantly, the separation of the solid and liquid phases is produced. These machines have yields of up to $65\text{ m}^3/\text{h}$ and, furthermore, it is possible to mount several units serially to reach higher yields. Service can be improved with a previous pass of the must through a sieve of revolving brushes. Also, to guarantee the centrifuge machine conservation, the must has to pass through a hydrocyclone that will eliminate sand particles that the must may contain. In Fig. 4.13 an installation for centrifuging must can be seen that includes a revolving-brushes sieve and a centrifugal clarifier; there is no hydrocyclone due to the presence of a previous decanting tank.

Figure 4.14 shows an installation made up of a revolving-brushes sieve, hydrocyclone, and centrifugal clarifier. If the liquids to be clarified contain high proportions of solids, it is better to apply centrifugal horizontal decanters that reduce that content to quantities not higher than 3%. In Fig. 4.15 a scheme of a centrifugal horizontal decanter is represented.

Filtration

The third finning procedure is filtration. This is nowadays the most used of three procedures. Revolving vacuum filters are the basis of this system. The turbid must is

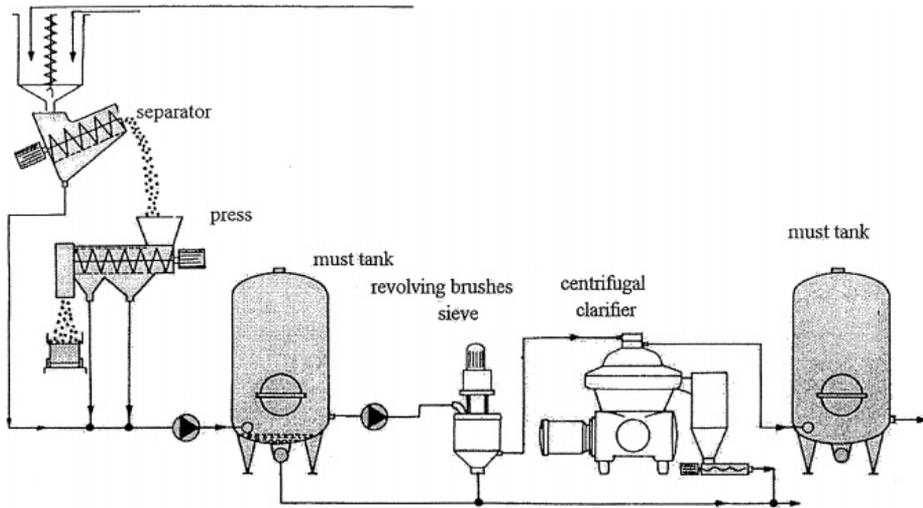


Figure 4.13. Installation for centrifuging must.

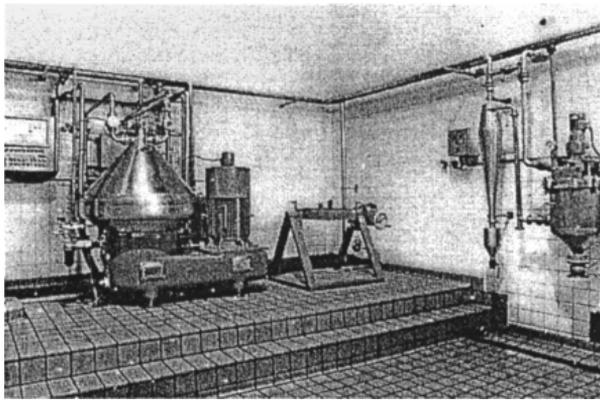


Figure 4.14. Installation of centrifugal clarifier.

forced to pass through a flour cap of diatomaceous earth, called *precoat*, which coats a horizontal drum partially submerged in a tank containing the must or wine to filtrate. The drum surface is maintained under vacuum during the process. The precoat retains the solid materials, which are detached from the drum by a cleaver, and the filtered must is channeled through the axial pipe. The yield of these filters is quite low, although it depends on the solids content of the must. It is fixed at approximately $0.3 \text{ m}^3/\text{h}$ per m^2 for musts with 4% of solids.

There exist filters from 2 m^2 to 40 m^2 of surface. Their operation can be continuous during 8 to 20 hours between successive precoat renovations.

It is possible to combine the described separation systems to obtain a final maximum-quality product.

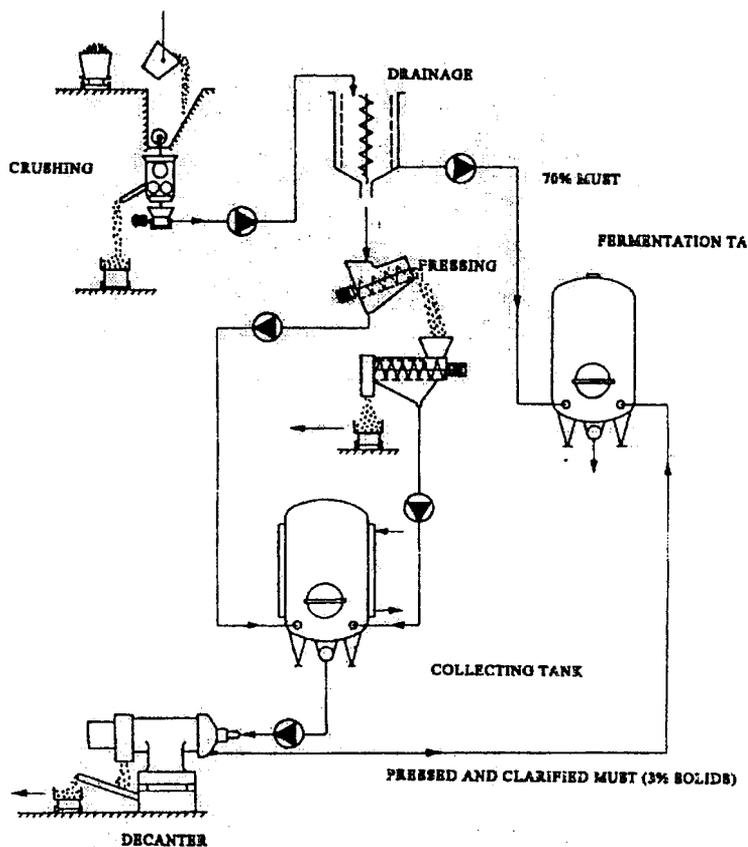


Figure 4.15. Centrifugal horizontal decanter system.

Fermentation

The must becomes wine after the fermentation. Fermentation is a complex process that is described very simply in this handbook. Fermentation happens in two stages. A first, called *tumultuous* or *primary fermentation*, is an aerobic process accomplished by yeast. These yeast can be present in the grapes or be selected by the winemaker. A certain quantity of air dissolved in the must is needed for development of the yeast. If fermentation bins or tanks are very large, there is little must surface in touch with the atmosphere and, as a rule, the fermentation is delayed; therefore it is necessary to accomplish bulk movement so that the liquid can dissolve some air. To achieve a good fermentation start, tank capacity must be approximately 20 m³. The name *tumultuous fermentation* is due to the fact that the bulk suffers an authentic boiling with heat and CO₂ production. In red-wine elaboration, this means an upward pushing of solids that remain floating on the surface, forming the “cap,” as long as the fermentation is active. Some fermentation tanks provide the possibility of automatically removing the cap to improve color and flavor formation, and others are horizontal tanks with continuous revolving movement (wine-making machines). During the process, temperature of the bulk is

increased, and gradually alcohol appears as a consequence of the glucose decomposition accomplished by the yeast. That alcohol is toxic for those microorganisms (the yeast), so that when it reaches a certain level it produces their inhibition, boiling detention, temperature decrease, and in red-wine processing without movement of the bulk, falling of the cap that rests on the bottom of the tank. In red-wine processing this is the moment for racking and pressing.

Temperature Control

In any type of wine elaboration it is necessary to have rigorous control of the fermentation process, with the purpose of avoiding excessively high temperatures of the bulk, which may cause accidents that can affect the quality and future “life” of the wine. Maximum admissible temperatures can be 30 to 32°C in red wine, and lower than 26°C in white wine (lower of 20°C for elaboration of fruity wines).

Temperature control of the tumultuous fermentation is accomplished, traditionally, through dosing in the must a certain quantity of SO₂, whose antiseptic characteristic is well known, and so inhibiting the development of the yeast. But quality-wine elaboration does not permit the abuse of sulfur dioxide employment, which communicates a certain bad flavor to the wine. Because of this, it is necessary to cool the wine by physical methods: the transfer of the heat excess, by radiation and convection, through the walls of the must tank directly to the atmosphere or to a water curtain that is made to slide by the walls of the tank. In either case, stainless-steel tanks in the open air are well adapted to this purpose. Figure 4.16 shows a group of fermentation tanks controlled by a cold-water shower.

If temperature control is not sufficient by this procedure, steel tanks with cooling circuits located in the upper part can be used. Through these circuits a cooling fluid

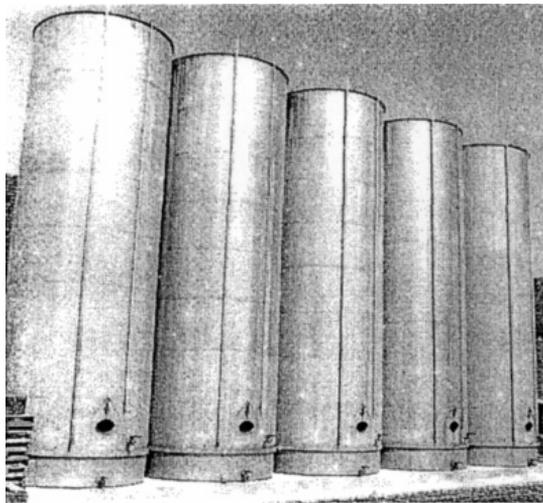


Figure 4.16. Tanks with cold-water shower.

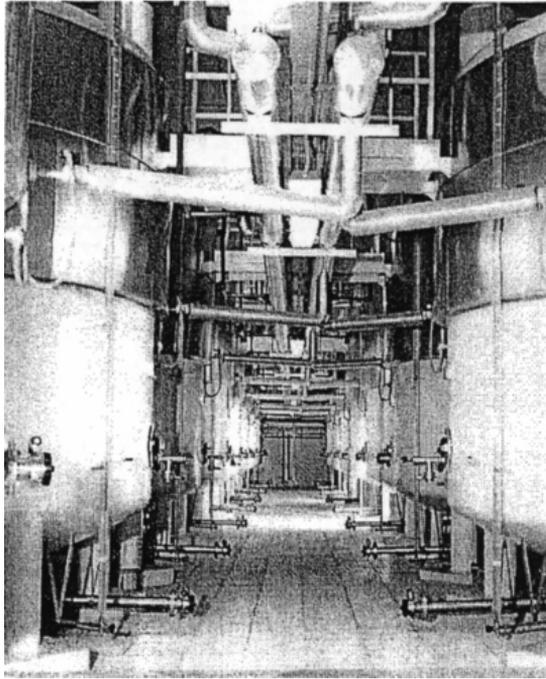


Figure 4.17. Tanks with refrigeration circuit.

circulates, from an adequate refrigerating installation. Figure 4.17 shows a group of tanks with refrigeration circuits sticking out of the upper zone.

If fermentation is made in tanks of low thermal transmission (concrete or wood), it is necessary to use other means to cool the bulk. One of them can be to introduce in the bin some plate heat exchangers, such as the one outlined in Fig. 4.18, in whose interior water is conveyed that has been previously cooled in an adequate installation. This system is usual in red wine fermentation, with bins containing the solid and the liquid parts of the vintage.

In white-wine elaboration, if the musts have not suffered a previous fining, as described previously, the cooling must be effected in coaxial-tube heat exchangers, such as the ones outlined in Fig. 4.19, where the must is refrigerated with cold water passing upstream; it must be assured that circulating space is sufficiently wide for the bulk to permit the solid particles that may be found in it to pass.

On the other hand, there are also autonomous equipment groups provided with refrigerators that use tube heat exchangers in stainless steel and cool the must with the coolant fluid circulating upstream. In Fig. 4.20 an equipment of such type is shown.

Finally, when the musts have been duly finned, even filtered, it is possible to employ plate heat exchangers as indicated in Fig. 4.21, which have better yields than previous equipment.

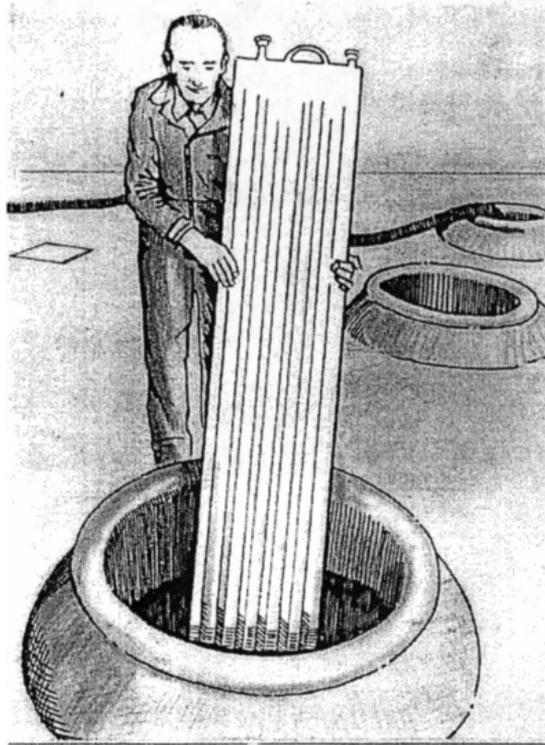


Figure 4.18. Mobile-plate heat exchangers.

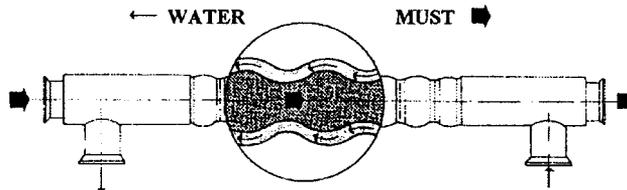


Figure 4.19. Coaxial tube heat exchangers.

Second Fermentation

Once tumultuous fermentation has finished, the must wine still contains certain quantity of sugar. The aerobic yeast that acted initially give way to anaerobic ones, which accomplish the second fermentation more softly and slowly than the first. At the end, the wine has been obtained.

There is a possibility of a second fermentation to obtain sparkling wine, that is, a wine with bubbles. Champagne is a specific regional name reserved for the Champagne region of France, but it is also produced in other areas (called “cava” in Spain). The second fermentation occurs in the bottle after a certain amount of yeast and sugar has

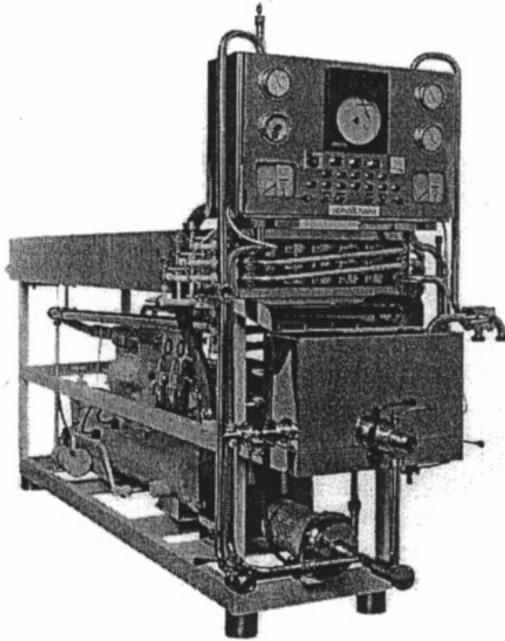


Figure 4.20. Tube heat-exchanger group.

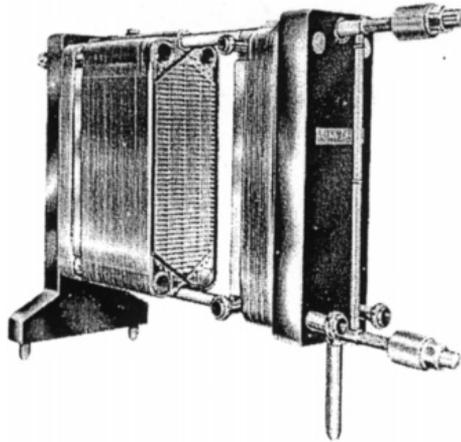


Figure 4.21. Plate heat exchanger.

been added to the wine. A movement of the bottle during this fermentation with a specific rhythm is needed to complete the process.

In some cases a process of “carbonic maceration” or whole-berry fermentation can be done, in which the grapes are not crushed and fermentation is performed inside the grape. The result is a fresh, light wine not appropriate for aging.

Storage, Aging, and Expedition

Some wineries are devoted to bulk wine production; others add the processes of bottling and, eventually, aging of wine. The former ones only have to consider a need to store the wine that may be solved in the same tanks used for fermentation or in different tanks. It is very common to use large tanks outside the buildings, of 1000 m³ or more, to keep the wine until marketing and distribution.

In those premises in which aging of wine is accomplished, the first operation is to transfer the wine to barrels of oak wood (until that moment of the elaboration process, tanks are made of concrete or steel), so that it acquires the characteristic flavors of tannin, vanillin, and wood. There is also some kind of oxidation because of the permeability of wood to oxygen. In these oak barrels the wine stays for a period of 6 months to 5 years, depending on type and final quality of the wine. During the time wine is in the barrel, temperatures must be constantly low and humidity high; also, the wine must be maintained resting quietly. This usually is done by maintaining it in underground cellars. Once the barrel aging is concluded, the wine is bottled and the aging process can go on inside the bottle. The aging in the bottle lasts more-or-less half of the time in the barrel (although there are exceptions such as Port wine, which can stay in the bottle more than 10 years before being sold).

Wine without aging goes directly to consumption after it is stabilized through refrigerating and filtering treatments, even pasteurized, and finally packed. Some wineries sell bulk wine to other wineries for blending, or to bottling industries or for distillation in alambic stills as a base for the manufacture of brandies.

At present, wines arrive to the consumer in packed form and, very rarely, in bulk form. Containers tend to be glass bottles for expensive wines, or carton bricks for cheaper wines. One way or another, it is required that previous treatments assure quality as well as stability.

Cold Application in Wine Stabilization

Cold can be used for the regulation of the must fermentation, as well as to guarantee the subsequent stability of the wine. In fact, the young wine contains certain substances that should be eliminated to assure its good quality. These substances are the following:

- Colloids and sludge, which can be extracted by centrifuging or filtering
- Pigments
- Yeast and bacteria, which can be extracted by filtering or using membranes
- Dissolved substances, which can be precipitated by variations in the wine temperature (bitartrates).

Bitartrates, which are dissolved at normal temperatures, can precipitate if the wine is cooled. This is the reason for eliminating these salts before bottling.

The best-known procedure for stabilization consists of submitting the wine to successive cold and filtration treatments. Cold treatments produce the tartrate crystals, and by filtration their elimination can be achieved. The system has many variants, according to the opinion of enologists. It is evident that the final wine quality depends as much on it as on the initial wine characteristics. In any case, it a process that lasts several days and implies an installation of certain importance.

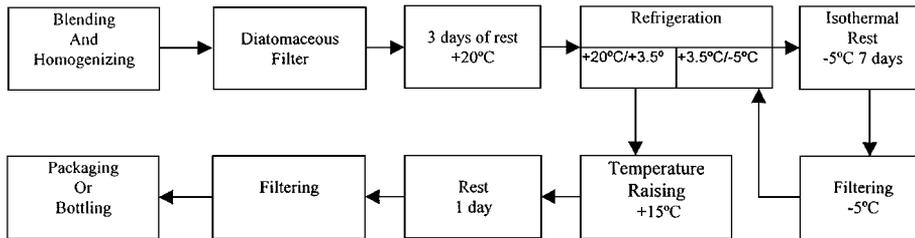


Figure 4.22. Flowchart of wine-stabilization system.

In Fig. 4.22 the flowchart of a wine-stabilization system of a certain complexity is represented, previous to bottling. It can be seen that the cooling of near to freezing temperature is the most important step to obtain precipitation bitartrates.

The process stages are as follow.

Blending and Homogenizing

Modern wines usually come from blends of two or more types, in adequate proportions. This blending can be done in a stainless-steel or polyester tank with agitator blenders and a minimum capacity of the daily volume of bottling. It is convenient to have at least two tanks, so that one can be filled while the other is emptying. Another solution is to have only one tank, but of double or triple the capacity of the daily treatment.

Diatomaceous Earth Filter. A filter is devoted to getting a first cleaning of the wine, extracting the sludge, colloids, and solid substances in suspension that may be contained. The yield of the filter must be at least the hourly bottling capacity (Fig. 4.23).

Three Days Rest. Some time of wine resting is advisable after filtering. Three days is considered adequate. So five tanks should be used, each holding the daily bottling capacity, so that one is filling, three resting, and the fifth supplying wine to the following stage.

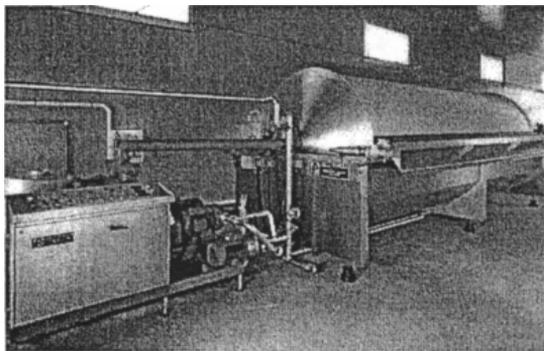


Figure 4.23. Diatomaceous earth filter.

Refrigeration. This is accomplished in two stages:

- Recovery, from approximately 20 to 3.5°C, in a plate heat exchanger passing upstream with wine already cooled. So, this phase means a thermal jump of $20 - 3.5 = 16.5^\circ\text{C}$.
- Cooling, from 3.5°C to temperature near freezing: for example, -5°C . The wine freezing temperature is approximately:

$$t = (\text{alcoholic degree} - 1)/2$$

For example, a wine of 13 alcoholic degrees will be frozen to -6°C , so it should not be cooled below -5°C . Consequently, the refrigerating power of the equipment must be:

$$q \times 3.74 \text{ kJ/kg}^\circ\text{C} \times (3.5 + 5) = q \times 31.79 \text{ kJ/h},$$

in which q is cooled wine flow (m^3/h), and the specific heat of the wine is $3.74 \text{ kJ/kg}^\circ\text{C}$.

Note that the recovery cooling does not have an energy demand, because it is considered a simple heat exchange. For cooling, refrigerating equipment is necessary whose condenser can be cooled by an air stream or by water. In the latter case, it is useful to install a recovery tower to save water.

Seven Days' Isothermal Rest. The wine at -5°C has to rest for easy bitartrate-crystal formation. This occurs in isothermal tanks, of stainless steel or polyester, with daily bottling capacity in each of them, of which there must be nine units (one being filled, seven in rest, and one being emptied).

Filtering. After the previous rest, once the bitartrate crystals are formed, wine is filtered to separate such crystals. A plate filter can be used with minimum yield for the bottling capacity.

Rise of Wine Temperature. The previous filtering has been made at -5°C , the same temperature at which the wine has stayed in the isothermal tanks. Now it has to return to a normal temperature; this is done by passing wine upstream, allowing the wine that enters to cool in the recovery section. If, for example, the final wine temperature has to be 15°C , the heat exchange will be:

$$3.74(15 - [-5]) = 74.8 \text{ kJ/kg}$$

higher than $3.74 \times 16.5 = 61.71 \text{ kJ/kg}$, necessary to cool the entering wine which yields a process efficiency of

$$61.71 \times 100/74.8 = 82.5\%.$$

Rest of 1 Day. This is accomplished in a tank with at least daily bottling capacity. It serves, furthermore, as stream regulation previous to bottling.

Filtering. This is the last process before bottling. It uses the same kind of equipment as in the previous step. Its yield has to be at least the daily bottling capacity.

Design Process of a Winery

An example of a real case is presented to illustrate the process of design. The case is the design of the cold installation needed to supply a wine-bottling plant that works at the rate of 10 m³ daily. Temperatures of the process would be those previously indicated. Requirements are as follow:

Treatment stream flow: for a shift of 5 working hours, 2 m³/h

Homogenizing and blending tanks: for example, two units of 10 m³

Diatomaceous filter: one unit with minimum flow of 2 m³/h

Three-day's-rest tanks: five units of 10 m³

Refrigeration

Recovery stage: plate heat exchangers; recovered cold: $2 \text{ m}^3/\text{h} \times 1 \text{ kg}/\text{m}^3 \times 3.74 \text{ kJ}/\text{kg}^\circ\text{C} \times 16.5^\circ\text{C} = 123.4 \text{ kJ}/\text{h}$

Cooling step: equipment must be able to facilitate $2 \text{ m}^3/\text{h} \times 1 \text{ kg}/\text{m}^3 \times 3.74 \text{ kJ}/\text{kg}^\circ\text{C} \times (3.5 + 5)^\circ\text{C} = 63.6 \text{ kJ}/\text{h}$; refrigerating power must be at least 71 kJ/h, considering a 90% efficiency

Seven day's isothermal rest: nine tanks of 10 m³ are needed

Plate filter: minimum flow of 2 m³/h

Wine temperature raising: done in the recovery section; wine increases its temperature from -5°C to 15°C , taking heat from the wine that is entering in the section, whose temperature goes from 20°C to 3.5°C , varying 16.5°C ; so, the heat exchange is $2 \text{ m}^3/\text{h} \times 1 \text{ kg}/\text{m}^3 \times 3.74 \text{ kJ}/\text{kg}^\circ\text{C} \times 20^\circ\text{C} = 149.6 \text{ kJ}/\text{h}$, and the taken heat is $2 \text{ m}^3/\text{h} \times 1 \text{ kg}/\text{m}^3 \times 3.74 \text{ kJ}/\text{kg}^\circ\text{C} \times 16.5^\circ\text{C} = 123.4 \text{ kJ}/\text{h}$, which implies an efficiency of 82.5%, as already had been calculated.

One day's rest: one or two tanks of 10 m³

Filtering: plate filter of 2 m³/h flow is needed

Installation summary:

- Tanks of 10 m³
- 2 units for homogenizing and blending
- 5 units for 3 day's rest
- 9 units for isothermal rest
- 2 units for 1 day's rest
- Total, 15 units
- Filters of 2 m³/h of flow: 1 diatomaceous, 1 of plates after isothermal, 1 of plates before bottling
- Recovery section by heat exchange of 2 m³/h of flow and exchange capacity of 150 kJ/h
- Cooling equipment of 71 kJ/h and 2 m³/h flow
- Pumps, pipelines, valves, etc. necessary to move the wine

Figure 4.24 shows an installation similar to the one described.

According to the previous text, stabilization process time is approximately 12 to 13 days. An important number of tanks and a large built space are required. In order to achieve a lower process time, as well as a reduction in the number of tanks, certain

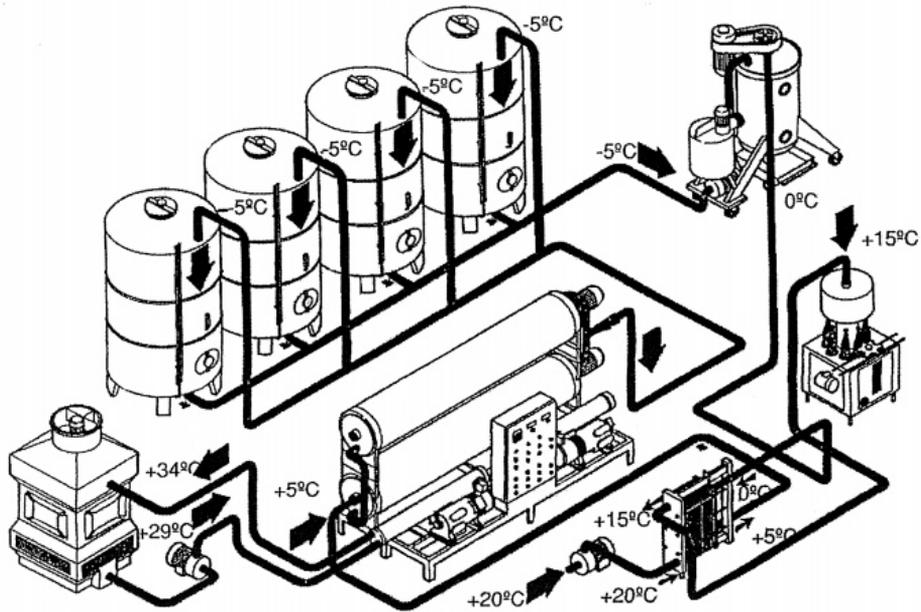


Figure 4.24. Cold-stabilization installation.

techniques that associate the application of cold with wine bulk agitation are being used. This causes immediate formation of bitartrate crystals, which afterwards are separated through filtration or centrifugation. These systems reduce the treatment time to 1 day.

It also must be taken into account that the example of a stabilizing plant constitutes a very complete case. More elementary installations with less intensive service are frequent.

4.1.3 Process and Winery Design Data

Design Data

Some average standard data for winery design are the following:

- Average wine/grape yield = 0.70.
- Average pomace/grape yield = 0.15.
- Capacity of the reception hopper: enough for 1 to 2 work hours.
- Density of the clusters in the reception hopper: 7 kN/m^3
- Density of the duly compacted pomace in pomace bins: 6.5 kN/m^3
- Density of the must wine: varies according to alcohol content; 10 kN/m^3 can be considered for tank and other process design

- Harvest duration: 15 days, more or less, unless special circumstances advise extending it. Working hours in the field as well as in the winery tend to be longer than 8 hours. These circumstances influence the capacity of processing machinery. Machinery capacities have to be selected taking into account these data, which may be obtained from previous experience or by programming the harvest.

Grape-entry volume grows from the beginning of the vintage until the central days, to descend at the end of the season. Because of this, in order to calculate the size and capacity of the elaboration machines, it can be assumed that on top days the intake is 20% to 25% larger than the season average. Finally, once the hourly processing capacity has been obtained, machines that reach it or surpass it slightly will be chosen. On the other hand, it is better to use two pieces of equipment instead of one alone, so a breakdown reduces production to half but it does not stop it entirely. Nevertheless, that solution is somewhat more expensive.

Fermentation Tanks

Good fermentation control needs tanks with capacity of approximately 20 m³, although larger tanks are used in some wineries.

Storage tanks

Storage and fermentation tanks are not differentiated in many wineries. But the existence of large tanks, not only for the annual campaign but also as interannual regulation of productions, is increasingly frequent. These are usually steel tanks, with capacities up to 1000 m³. The presence of these tanks is more frequent in nonaging wineries.

4.1.4 Design Example

A winery that is going to receive a 30,000 kN grape crop has the following requirements:

Winery capacity: $30,000 \times 0.7 = 21,000 \text{ kN} = 2100 \text{ m}^3$

Pomace volume: $30,000 \times 0.15 = 4500 \text{ kN}$; $4500 \text{ kN}/6.5 \text{ kN/m}^3 = 692 \text{ m}^3$

Machinery design: average elaboration yield, $30,000 \text{ kN}/15 \text{ d} = 2000 \text{ kN/d}$;
top days, $1.2 \times 2000 = 2400 \text{ kN/d}$; hourly capacity, $2400/8 = 300 \text{ kN/h}$.

Process machinery can be selected with this capacity and also with 150 kN/h; therefore, it is possible to adopt a group of machines of 300 kN/h or two groups of 150 kN/h

Fermentation and storage tanks: $n = 2,100/20 = 105$ tanks; it is convenient to add a 5% more as safety margin—that is to say, 110 tanks of 20 m³ are needed in the winery

Grape-reception hopper, triangular base section 5 m and depth 2.50 m: capacity by meter of hopper, $0.5 \times 5 \times 2.50 \times 7 \text{ kN/m}^3 = 43.75 \text{ kN/m}$;
for operation of the machinery between 1 and 2 hours, $1.5 \times 300 \text{ kN/hr}/43.75 \text{ kN/m} = 10\text{--}11 \text{ m}$ of hopper length

Labor and costs: Labor needs for the example winery can be three permanent people, two for quality control and one more in the process section. Two

more would be needed during the harvest time. Cost of machinery could be of US\$300,000, varying greatly among different countries.

4.1.5 Winery Description

A more complete winery description can be seen in Ref. [3].

Reception Hopper

This is usually built of concrete or reinforced concrete. The surfaces are polished or covered with glazed tiles or better with stainless steel to facilitate the flow of the grape clusters. The hopper walls project up from the soil 0.25 or 0.30 m to avoid entrance of rainwater reflected by the contiguous pavement. The dihedral faces have equal slopes if two worm screws are used and unequal if only one. So, clusters vault and empty operation of worm screw will be avoided. In no case is wall slope less than 45 degrees. The set is covered with a roof whose supporting structure is located so that it does not block vehicle circulation.

The use of this type of hopper implies that cluster dumping must be made by hand or the use of self-dumping transportation vehicles. But in some areas grape transportation is made by tows provided with canvas or plastic, on which clusters are loaded. So, it is very convenient to have mechanisms that facilitate dumping. Among them is the unloading tipping platform, as shown in Fig. 4.3, which consists of two pieces one after the other. The placement maneuver of the tow is thus simplified: One of the platforms is placed over the hopper and acts as bridge to get the tow pass over, until it is located on the other platform. Afterwards, both are lifted and the grape falls between them, just within the hopper. Also, hydraulic jacks can be found that incline the vehicles to facilitate dumping, although damage can be caused to the tow if these are not properly operated.

Another solution consists of having a sole unloading tipping platform near the hopper that is lifted parallel to it, which facilitates tow dumping by one of its sides. In some wineries with little space for vehicle movement, grape aspirators have been successfully installed. The aspirator has a mobile mouth that can reach any point of a shipment located under it. Such a mouth is fitted to a flexible pipeline that ends in a potent cyclone, which absorbs the clusters through the mouth and pipeline and exhausts them onto the crusher, located below, by the air expansion during entry in the container. Naturally with this exhaust system the receipt hopper is not needed; therefore it can be adapted to wineries with scarce space.

In most cases, the reception hoppers are built, with platforms as well as without them, isolated from the remaining buildings of the winery, so that they will be accessible from each of their sides.

The centrifugal crushers receive the clusters from the lower part; therefore, the placement of these machines requires a perfect alignment between the shaft of worm screws and the shaft of the crusher's orifice. In other models the grape is received by the upper part, which makes it necessary to dig large pits to place the crusher. A building is made to locate the crusher and the vintage pump, the dimensions of which are dictated by those machines.

Press Room and Pomace Bins

The press room is designed in agreement with the drain and press machines. If there are pomace bins, they are located adjacent to the press room so that the pomace passes directly from the presses to a by-pass that distributes it into different bins. Otherwise, if there are no pomace bins built, it can be designed a container or hopper elevated over the floor. This hopper is loaded through a worm screw, which collects pomace from the press exit. Hopper emptying is done through openings in its base into by-product transportation vehicles, which can pass under the hopper.

In wineries with red-wine elaboration it is convenient to have the press room next to the storage building. So, according to what has been said, once the first fermentation has finished the must wine passes to drain and press machines. Therefore, proximity of tanks to these machines is necessary.

If the elaboration is only of white and pink wines, the press room and pomace bins can be built separate of the other buildings. This facilitates access to all buildings and possible winery amplifications.

The machines of the press room, one or several, are as follow:

- Vibrator or static drain hopper
- Separator presses
- Presses
- Pomace evacuator (in general a crusher, collector, elevator, and distributor)
- Transferring pumps

As has been shown, three or four must classes are obtained that it is advisable to separate. For this reason underground sumps are built. To those sumps hoses from each one of the press machines are conducted. The whole capacity of the sumps must be equivalent to the hourly must production, and their number depends on the selection degree made with musts or wine. There are at least two units. Thereafter, the must is pumped separately to the fermentation tanks in white-wine processing or to storage in red-wine processing.

Construction of Press Room

The press room is of simple construction. Mass concrete or slightly reinforced concrete is used in foundations, benches, and the ground floor. The floors are smooth with good drainage to avoid puddles. The structure is of reinforced concrete, steel, or any other material adapted to the building dimensions. There are simple walls of conventional type, roof with thermal insulation of sufficient quality, metallic doors easy to handle and of dimensions adapted for installed machines, windows of concrete, metal, or PVC with enough opening to guarantee ventilation; good light, natural as well as artificial (300–500 lux); and power take-off in accordance with the installed machines. Even the general switchboard of the winery could be installed in this room, with the proper security measures. Plenty of pressured water is needed in this room. The sewer system is minimal, an inspection chamber for cleanliness of water being enough. Towards this inspection chamber the floor inclination is directed.

Pomace Bins

Pomace bins are built of mass or reinforced concrete, with a depth not larger than 5 m to avoid difficulties in pomace extraction, or even smaller if a high water table is

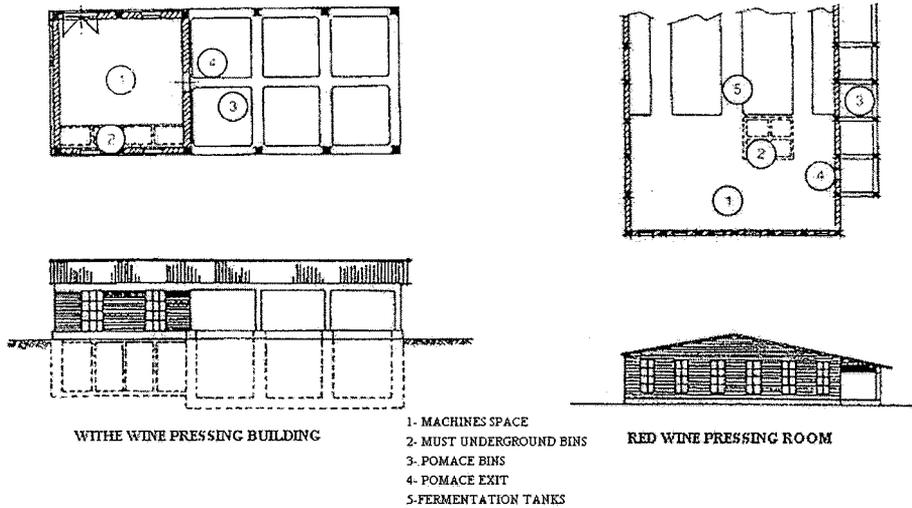


Figure 4.25. Press buildings.

present. Placement of bins in double string is advisable, because this permits location of the pomace unloader in the central wall, so that it can unload to the right and left. Direct access from outside to the bin strings is necessary. If pomace bins are designed adjacent to a press-room wall or to a loading-wharf wall, it will not be possible to have that arrangement, and only one string should be built. As a rule, bins are covered with a light roof; their lateral façades can remain open or be closed with simple walls with the necessary openings.

In wineries that employ reduced-pressure presses, the pomace depletion does not become complete; therefore it is usual to have “purge sumps” in pomace bins in simple inspection chambers in accessible corners, toward which is the inclination of the floor of the bin directed. So the fluids from the pomace remain isolated from solids and in contact with the open air through a brick chimney. Two press-room models are represented in Fig. 4.25. The first corresponds to a white-wine winery and, together with the pomace bins, forms a set of equipment isolated from the rest of the winery constructions. The second belongs to a red-wine winery; the press room is near the storage room. At the same time pomace bins are adjacent to both rooms. In both models pomace bins can be replaced by an elevated steel hopper in case of continuous pomace removal.

Storage Room

Must storage, fermentation and subsequent conservation of the wine can be effected in a storage room, which can be a building or section of a building. In all cases the storage room is full of tanks on the ground floor, and in some wineries underground bins as well. Storage-room dimensions are fixed according to the number of tanks and their characteristics. The storage room must have the following conditions.

Insulation

There must be good cover and wall insulation. Transmission coefficients should not be higher than 2.9 and 4.15 $\text{kJ/m}^2 \cdot \text{h} \cdot ^\circ\text{C}$, respectively.

Ventilation

Good ventilation is necessary at all levels to facilitate the carbonic anhydride exhaust produced during the fermentation. This gas is heavier than air and will remain in the lowest parts of the room. Because of this, holes at that level are advisable and, eventually adequately situated air fans will have to be installed. Mobile fans that can solve deficiencies in a wrongly projected ventilation system can be found.

Tanks

With the on- and underground tanks there must exist a great bin, preferably underground, intended for blends or “coupages.” Its capacity is more than five tanks. It is located in an area of easy access to tankers for direct wine charge. It is also necessary to have several small tanks whose added capacity is the same as one storage tank and that are destined for withdrawal of wine excess during emptying of larger tanks.

Drain Pipes

An adequate net of drainage pipelines for evacuation of cleaning waters must be designed. However, if some or all of the surface is occupied with underground bins, pipeline tracing is hindered and the net is limited to one drain pipe located in a transverse sense and toward which the longitudinal channel opened over the top slabs of the underground bins is directed. In small wineries the absence of a sewer net is frequent; a set of interior channeling that ends in an underground bin is enough. Washing the winery before each elaboration, the foul waters are collected in that bin and pumped outside. The underground bin can be cleaned and prepared also to receive wine from overflowing or other tanks breaking.

Other Buildings and Facilities for Storage

The storage shed as well as the other winery buildings should have an adequate distribution network of drinking water. Winery water needs are not very important, except in the cases of the bottling section and the consequent bottles washing.

In some wineries large outdoor steel tanks are built for partial storage, complemented with a building for smaller tanks. All storage can be done in large tanks. In this case there is not a storage building. An area for the manipulations previous to expedition is needed.

4.1.6 Tanks

Only descriptive aspects are mentioned here. Structural design of tanks can be seen in Ref. [3].

Wall Materials

The tanks can be constructed of ordinary steel with internal anticorrosive finish, stainless steel, reinforced concrete, reinforced polyester, or oak wood.

Position and Construction

In relation to their position in the storage room, they can be on the ground, that is to say built on the soil level; or underground, or built under the average level of the winery.

As a rule, underground bins are reinforced concrete; on-ground tanks can be of concrete, steel, polyester, or wood. The last, the most expensive, mainly are used in wine or liquor aging. They are not used in the wineries that sell wine less than a year old.

Tank construction, of any material and shape, is subject of a certain specialization; experts must be relied on for quality.

With respect to the most convenient material and shape of tanks, it can be said that for racking and first fermentation steel or reinforced concrete tanks are preferred, on the ground and with low manholes that are used to extract the solids. Their capacity should not be excessively large, for a better fermentation control, 20 m³ is adequate. Cylindrical tanks present the advantage of remaining isolated from each other by a space never smaller than 0.5 m, which permits avoiding fermentation interaction between tanks. On the other hand, they demand larger building surface. Stainless-steel tanks, although somewhat more expensive, are the most common because of their hygienic conditions. Prismatic tanks, generally of reinforced concrete, are built in sets of several units, so that their walls are shared between two tanks. That circumstance makes it advisable to establish insulation joints to create groups of units in contact, with a whole capacity of near daily must production. For example, if the mean elaboration of a winery is 200 m³ daily and fermentation tanks are 20 m³, the insulation joints should be created every 10 tanks, so only tanks filled on the same day are in touch, in which fermentation processes are similar.

For secondary fermentation and wine storage any type of tank can be used.

Advantages and Disadvantages

Among concrete tanks, cylindrical are more economical than prismatic. The first require a greater space and the accomplishment of a high floor for manipulations. This can be saved in the prismatic tanks; for this purpose the upper slab is used. However, the total investment is lower with cylindrical tanks because of lower structural loads.

As a rule, underground tanks are prismatic and of reinforced concrete. Their walls are designed to resist liquid and earth loads, as well as the loads exerted by the next foundations. Because of their underground placement they maintain a uniform temperature throughout the year; therefore, they are very recommendable for storage of wine that stays in the winery during summer.

Steel tanks are usually cylindrical and can be of great capacity, which makes them very adequate for storage. They can be installed in a vertical or horizontal position, which is a very important facet of their design. The first arrangement takes better advantage of the space; the second permits installation in two or more levels, after adequate structure construction (Fig. 4.26). Stainless-steel tanks increase investment, although they provide an extraordinary conservation guarantee of the content as well as of the tanks themselves. The advantages that steel tanks present for the fermentation control have been indicated previously; they are a consequence of the high thermal transmission of their walls, which allows shower refrigeration or refrigeration through a fixed cooling circuit, as well as, if necessary, a heating circuit to enhance the start of fermentation in cold zones.

Glass fiber-reinforced polyester tanks have been used increasingly for some years now. This is a material resistant to nearly all chemical agents, easy to clean, and very economical (Fig. 4.27).

If thermal insulation is required in steel or polyester tanks, they are lined with an adequate insulation material (polystyrene, polyurethane, mineral fibers, etc.) and also an external wrapper of steel or plastic.

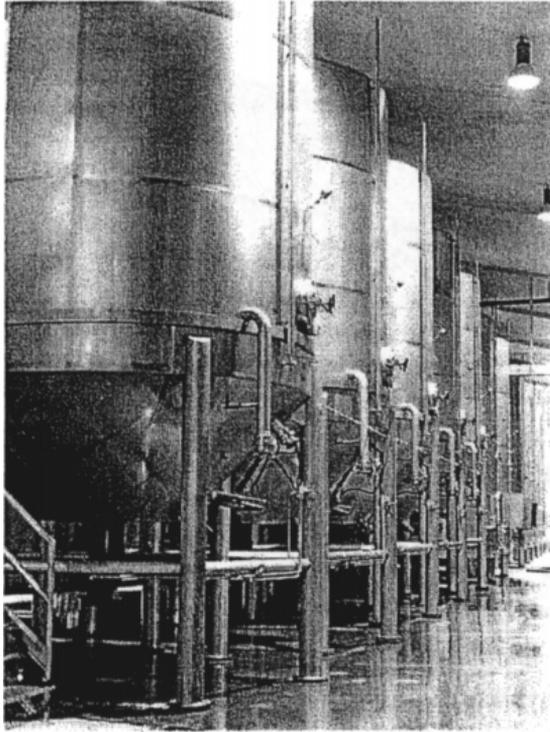


Figure 4.26. Vertical steel tanks.

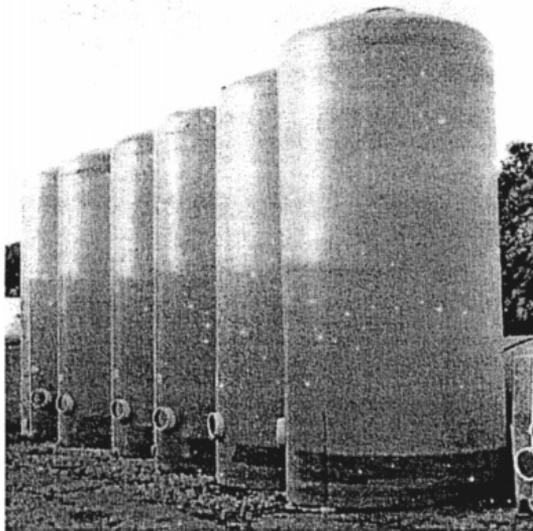


Figure 4.27. Polyester tanks.

Wood containers are an expensive investment but are essential for good wine aging due to their walls' porosity, which enhances a very slow oxidation, the basis of the aging process. These barrels are made by coopers who reside in certain wine regions of strong tradition.

References

1. Peynaud, E., and A. Spencer. 1984. *Knowing and Making Wine*. John Wiley & Sons, New York.
2. Jackson, R. S. 1994. *Wine Science: Principles and Applications*. Orlando: Academic Press.
3. García-Vaquero, E., and F. Ayuga. 1993. *Diseño y construcción de industrias agroalimentarias. (Design and Construction of Agroindustries)*. Madrid: Mundi-Prensa.

4.2 Olive-Oil Processing

E. Garcia-Vaquero and P. J. Aguado

4.2.1 Olive Composition

According to Civantos *et al.* [1], the average composition of an olive when it is harvested is

Vegetative water, 40% to 55%
 Oil, 18% to 32%
 Nut, 14% to 22%
 Seed, 1% to 3%
 Epicarp and rest of the pulp, 8% to 10%

The average composition of fatty acids in the oil is

Oleic acid, 63% to 81%
 Linoleic acid, 5% to 15%
 Palmitic acid, 7% to 14%
 Stearic acid, 3% to 5%
 Arachidic acid, 1% to 3%

Olive oil also contains 0.5% to 1% unsaponificables particularly rich in beta-sitosterol and squalene.

Other vegetable oil's compositions are as follows

Sunflower oil

Linoleic acid, 70%
 Oleic acid, 16%
 Palmitic acid, 7%
 Stearic acid, 4%
 Unsaponifiables, 1%

Coconut oil

Lauric acid, 39% to 54%
 Myristic acid, 15% to 23%
 Caprylic acid, 6% to 10%
 Palmitic acid, 6% to 11%
 Capric acid, 5% to 10%
 Oleic acid, 4% to 11%
 Stearic acid, 1% to 4%
 Linoleic acid, 1% to 2%
 Unsaponifiables, 0.6% to 1.5%

Soybean oil

Linoleic acid, 46.2% to 52.6%
 Oleic acid, 21.9% to 26.6%
 Palmitic acid, 9.5% to 12.2%
 Linolenic acid, 7.9% to 8.5%
 Stearic acid, 4.9% to 6.1%
 Unsaponifiables, 0.5% to 1.6%

4.2.2 Industrial Process

In Fig. 4.28 several stages of the industrial process are shown.

Reception, Cleaning, and Control

When the olive shipment arrives to the processing plant, olives must be cleaned because they contain leaves, branch pieces, nuts, and so forth. A machine based on vibratory sieves can be used for this purpose (Fig. 4.29).

Quality control consists of selection and classification of the incoming product into quality classes, in a sample extracted through different ways. The classes selected consist of variety, damages caused by insects or mechanical damage, ripeness, and so forth.

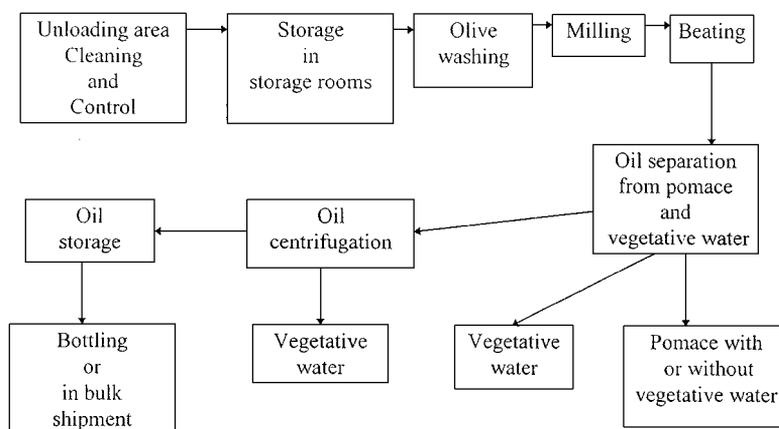


Figure 4.28. Process flowchart.

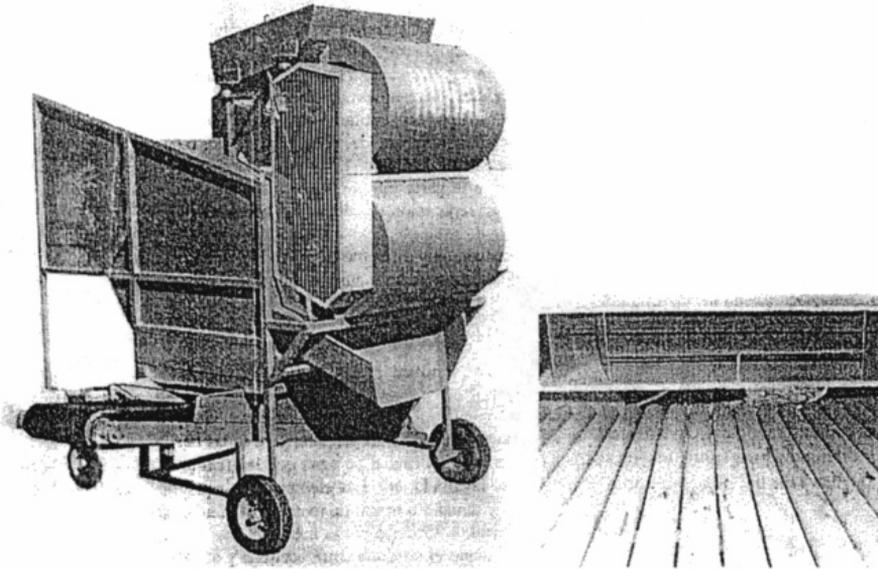


Figure 4.29. Hural cleaner.

Each load has to be controlled by weighing it in a hopper scale. The hopper with a capacity for 1 or 2 tons is fixed on a platform that transmits the measured weight to the control post at the entrance of the processing plant.

Olives are carried from the initial hopper to cleaning and control by rubber conveyor belts with a suitable slope and length (Fig. 4.30).

Storage Containers

When the olives leave the hopper scale, they are carried by a conveyor belt to the storage containers (Fig. 4.31). In the new industries, storage containers are large hoppers made of steel sheets with enough capacity for the volume that the industry can process in 2 or 3 days. In this way the production does not stop when olive shipments do not arrive due to bad weather or other reasons. That is also a reason why during the oil-production season industries work 24 hours without interruption.

Olive Washing

Recently harvested olives carry soil, mud, and other residues. Therefore they must be washed before their elaboration.

Olives are washed twice, first with water when olives are in the hopper of the washing machine (Fig. 4.32), and second with a water bath. Finally, olives leave the machine on a wire-mesh conveyor to remove the water.

Milling

Milling is done using a hammer mill (Fig. 4.33). The olives, after leaving the washing machine, come into the milling chamber, where the hammers spin at high speed. Hammers throw the olives onto the perforated steel shell. Paste passing through the shell is dragged out by blades to ease the exit of the paste across the openings.

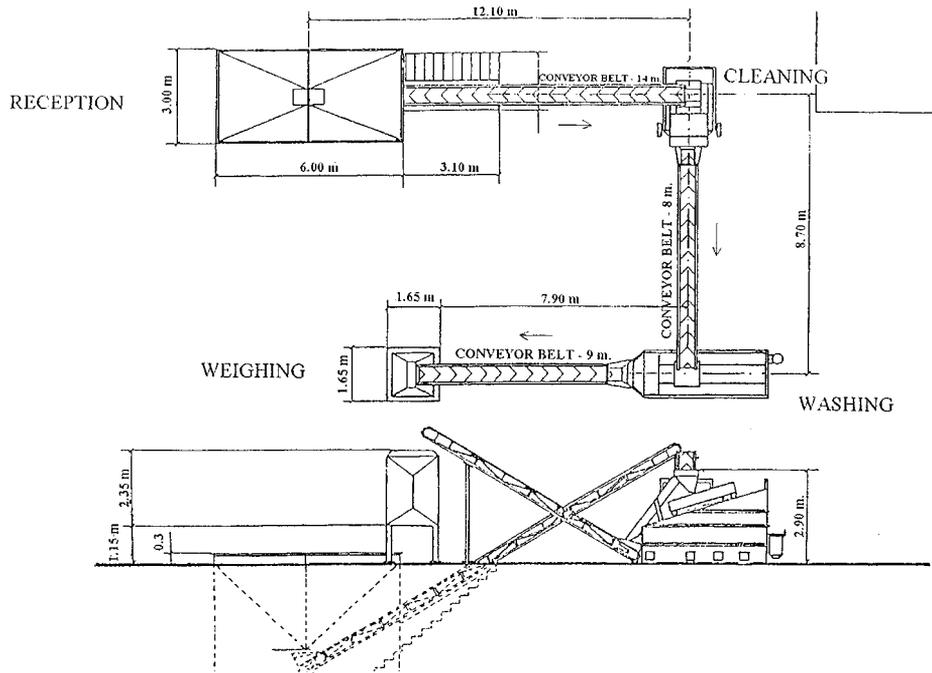


Figure 4.30. Common reception, cleaning, washing, and control system (Hural system).

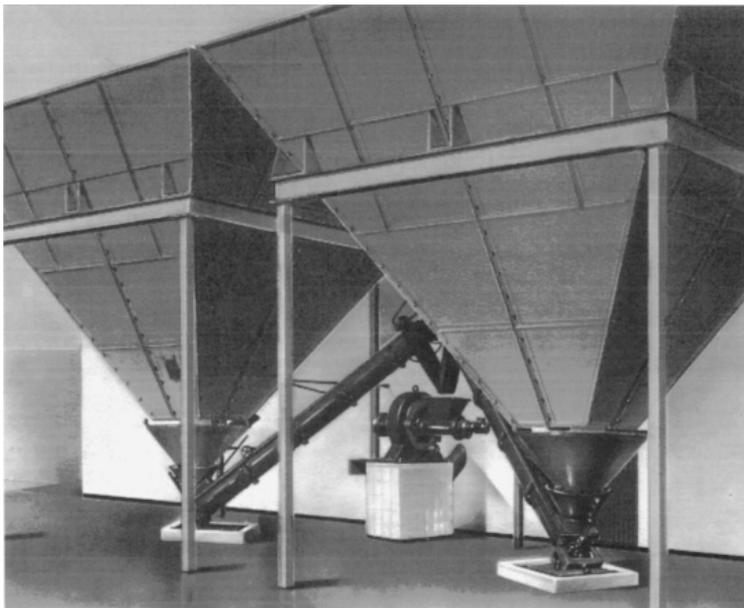


Figure 4.31. Storage containers. Olives are stored before they are milled.

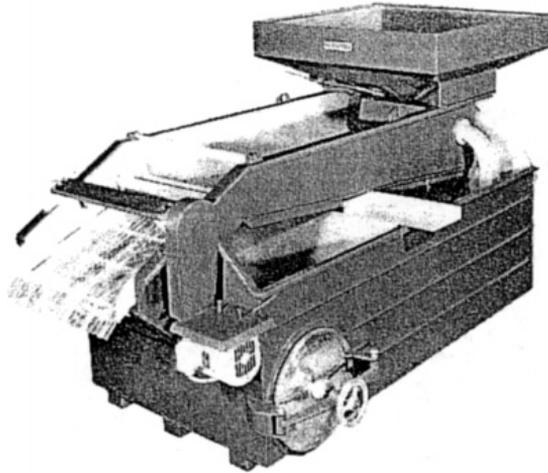


Figure 4.32. Pieralst olive washing machine.

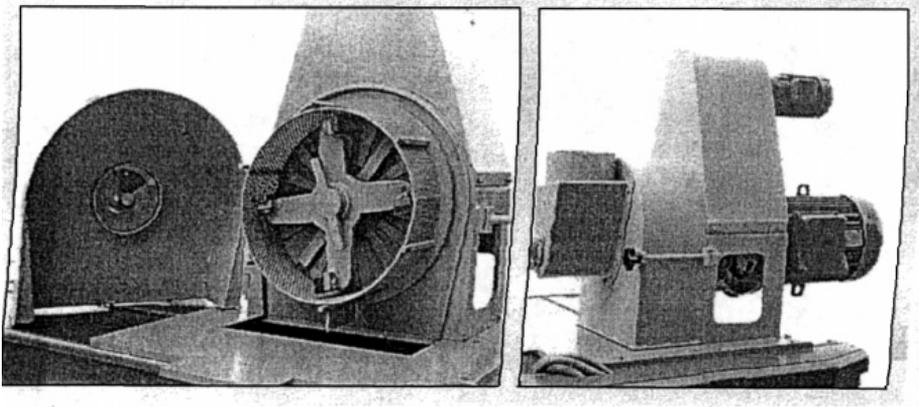


Figure 4.33. Olive mill. This machine crushes the olives using blades with hammers.

The old “rulos” mills or stone rollers have been replaced by the hammer mills. Nowadays few industries still use the first ones.

Heat Beating

Vegetable fat must be reduced to facilitate the grouping of the oil drops and to enhance the removal of the oil from the rest of the paste. Vertical and horizontal beaters are used (Figs. 4.34 and 4.35). Vertical beaters have a cylindrical shape with two concentric shells. Between these two shells hot water flows to heat the paste. Heat convection is increased by small spinning shovels.

Horizontal beaters have a semicylindrical cross-section. They have also double-shell and spinning shovels to heat the paste. Two or three of these beaters can be placed in “cascade” to improve the yield.

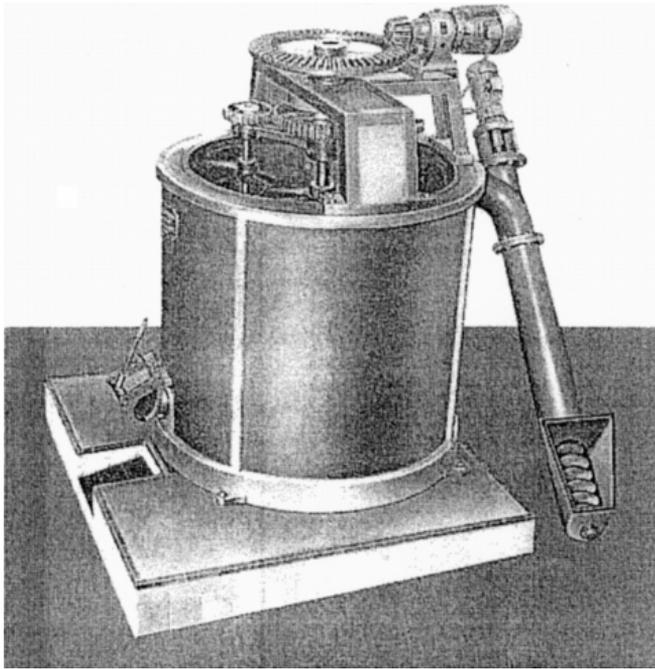


Figure 4.34. Vertical beater. This machine increases the drop size of the paste to make easier the subsequent oil extraction.

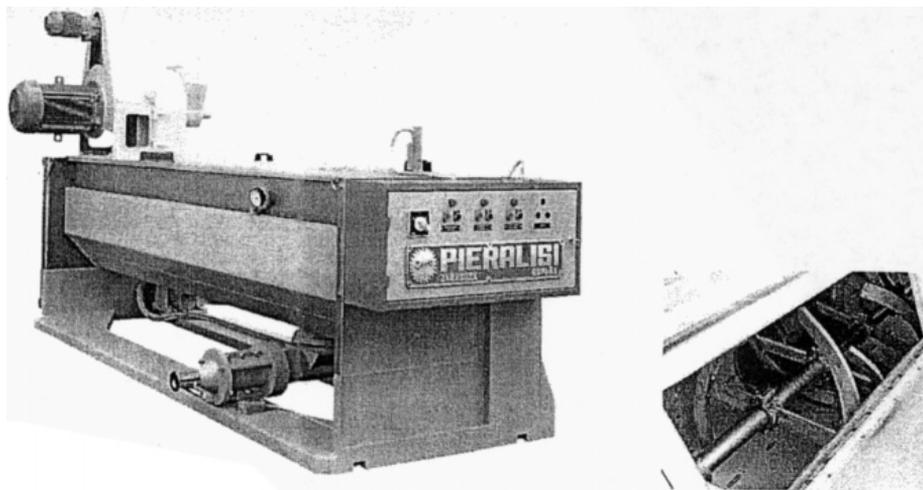


Figure 4.35. Horizontal beater.

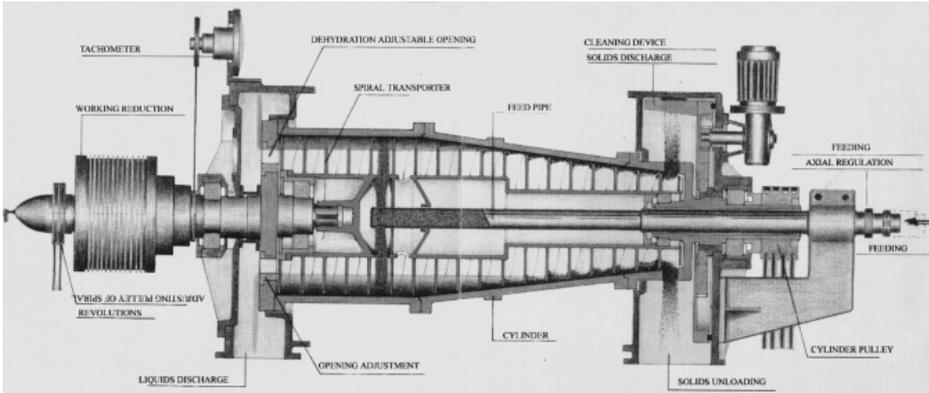


Figure 4.36. Decanter (Horizontal centrifuge). This machine separates the three phases of the beaten paste (oil, vegetative water, and pomace) or the two phases (oil and vegetative water, and pomace).

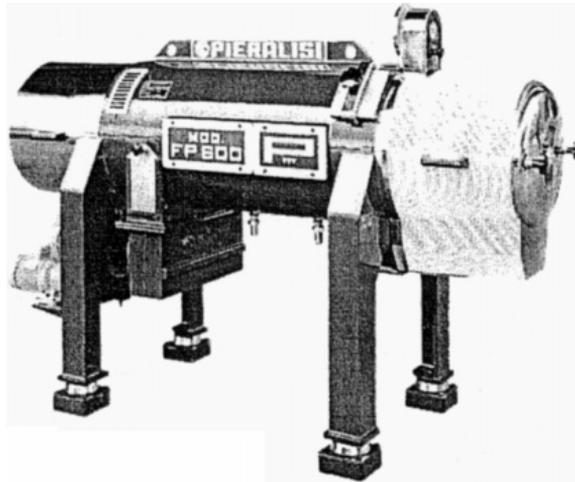


Figure 4.37. Decanter (horizontal centrifuge).

Depending on the olive moisture content it may be necessary to add water to increase fluidity of the paste. Beating takes approximately 1 hour.

Oil Separation

Beaten paste is pumped to a horizontal centrifuge that must add cold and hot water, about 30% to 60% of the mass, to facilitate the separation.

Horizontal centrifuges (Figs. 4.36 and 4.37), also called *decanter*s, separate the three phases of the beaten paste. Because of the centrifugal forces, components with higher bulk densities (solids or pomaces) are located in the periphery and are extracted through

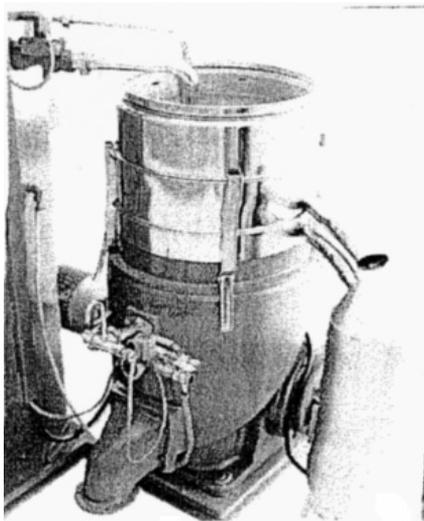


Figure 4.38. Vertical centrifuge, where oil-vegetative water separation is completed.

one end. The intermediate bulk density phase—vegetative water with the water added to facilitate the paste pumping—stays in between and comes out through an opening. Finally, the lighter phase, that is, the oil, stays in the center and comes out through the corresponding opening.

Therefore, the horizontal centrifuge forms, from the center to the periphery, three concentric rings with solids, water, and oil. The separation is not perfect, however, so zones with a mixture of phases appear in between. Therefore pomace comes out mixed with a part of vegetative water and, as a consequence, the moisture content of the mixture is 50%. On the other hand, vegetative water will carry some oil and, obviously, oil will carry some vegetative water, so the separation has to be completed.

This second separation is carried out in vertical centrifuges (Fig. 4.38). As a result, vegetative water is largely degreased and oil is extracted without water.

Because the subsequent vegetative water removal is a serious problem, because it is very polluting, many oil industries adjust the decanter in a way that most of the pomace and vegetative water are extracted together. This way, the problem is passed on to the extraction industries, which have to dry the pomace before the olive-oil extraction. That involves evaporating the vegetative water with a high energy-input increase. To make this process cheaper and more environmentally appropriate, the “orujillo” (pomace after fat is removed) is used as a fuel.

4.2.3 Olive-Oil Industries

The olive oil industries are called in Spanish *almazaras*, a word of Arabian origin (*al-massara*) that means squeezing place.

Olive-Oil Industries Outputs and Design Data

From every 100 kg of milled olives, after removal of impurities that came with the olives, the following products are obtained:

Clean oil, up to 26.5 kg

Vegetative water without olive oil, 76.5 kg

Pomace (moisture 50%, oil 4%, solids 46%), 42 kg

Total, 145 kg

(It must be taken into account that cold and hot water are added to the beaten mass before entering the decanter).

Further data are as follows:

1 m³ of olives weighs 630 to 650 kg

1 m³ of pomace (moisture of 50%) weighs 750 kg

1 m³ of olive oil weighs 920 kg

The olive-harvesting season lasts between 30 and 60 days, depending on the weather and other circumstances during the year. Olive-oil processing plants work between 40 to 60 days, 24 hours per day, from which only 20 are effective.

There are two types of storage tanks: inside tanks and outside tanks. Inside tanks are placed inside the oil-olive cellar, and their capacity is from 10 to 50 m³. Outside tanks are of the silo type, and their capacity is 500 m³, or more.

Processors in this economic sector do not like open-air tanks; nevertheless, these are becoming very common due the lower investment needs for buildings and space. They must be constructed of stainless steel but can also be built using steel with a protecting coating inside.

Description of an Olive-Oil Processing Plant

Equipment can be installed inside or outside the building; therefore, outside and inside equipment can be distinguished.

Generally, heavy and cleaning equipment, as well as storage containers, are built in the open, while the rest are placed indoors.

These buildings have the following areas.

Processing Area

The processing area has mills, beaters, decanters, and vertical centrifuges, as well as pumps that pump the oil to the storage tanks. Buildings can have rectangular shapes with enough space for the machines and staff activity. A height of 4 m is sufficient.

Because beaters need a heat supply, this is enough to heat the processing area. In any case, the temperature must not be less than 18°C.

In the process room, the floor is constructed of materials that resist corrosion by liquids produced in the industrial processes. It must be also washable, nonslippery, and easily repairable. It must have sewers and suitable slopes (1%) to drain the washing water. Walls are constructed of smooth, washable and easily repairable materials. In older times, the lower 2.5 or 3 m, at least, of the walls usually was covered with tiles. Currently it is covered with continuous coverings, such as epoxy resins, which are more effective but a little less esthetic.

Ceilings should be smooth and of easy cleaning. Aluminium and prelacquered steel sheets can be used. It is very important to have a good heat isolation. For water and electrical installations, pipes and electrical ducts must be uncovered and suitably protected and provide easy access. Usually, natural ventilation is adequate. Otherwise, ventilation equipment has to produce total air exchange 10 times per hour. There should be natural or artificial illumination of approximately 400 to 500 lux.

Oil-Olive Cellar and Storage Area

It has been mentioned that olive oil can be stored in outdoor or indoor tanks. Plants that store it indoors place the tanks in a special building. Generally, the cellar is a shed joined to the processing room to facilitate the oil transfer.

Storage capacity can be the annual harvest or only a part of it (if the plant sells and produces the oil simultaneously). Anyway, the different harvests of each year make it very difficult to calculate this parameter. Some details of the olive-oil cellar design can be mentioned: Floors, walls and ceilings are similar to those used for the process room, but the top layer need not be so fine. Preferably, the cellar will have low natural illumination, but on the other hand, it is necessary to have sufficient artificial illumination for the works carried out in this room (50–100 lux). In the same way as for the processing room, pipes and electrical ducts must be uncovered but suitably protected. Heating is essential for good oil preservation. The temperature inside the cellar must not be less than 18°C.

Additional Facilities

Besides the mentioned buildings, which are the main parts of the processing plant, the following facilities must be available:

- A cabin for the scale arm and the person who controls it; entrance and unloading area must be controlled from it
- An office, size of which depends on the industry size and importance
- A laboratory for the necessary tests for oil elaboration and storage
- Bathrooms and changing rooms for the staff during the oil-production season and for the rest of the year.
- A room of suitable size where the water heating is located; hot water, at a temperature of 80°C, is essential for the elaboration process and for ambient heating; if “orujillo” is used as fuel, a storage facility must be built close to the previous room, with capacity covering the needs for a 2-week working period.
- A separative sewer net, that is, vegetative water and rain water are piped separately; the first must be piped to a pond, with waterproof walls, from which it will be periodically extracted for depuration or removal to a suitable community installation; rainwater and wastewater from the bathrooms are piped to the town’s sewers.
- Finally, surface for all installations, which must be mostly paved to facilitate the access and parking of the olive- and oil-transport vehicles; must be fenced to avoid trespassing.

Example of an Olive-Oil Processing Plant

A sample for an olive-oil plant for $2 \cdot 10^6$ kg of olives is as follows

- i) Productions (three phases: oil, vegetative water and pomace):
 Oil - $2 \cdot 10^6 \times 0.265$ (See 3.1) = 530,000 kg
 Oil Bulk Density = 0.92 kg/l
 Oil Volume = $530,000/0.92 = 576,086$ l
 Vegetative water without olive oil = $2 \cdot 10^6 \times 0.765$ (See 3.1) = 1,530,000 kg
 Pomace (moisture content of 50%) = $2 \cdot 10^6 \times 0.42$ (See 3.1) = 840,000 kg
- ii) Processing season length = 40 days.
- iii) Facilities:
 Processing = $2 \cdot 10^6$ kg/40 days = 50,000 kg/day
 Machinery performance (See 3.1) = 50,000 (kg/day)/20 (h/day) = 2,500 kg/h
 Boiler performance = 335,000 to 420,000 kJ/h
 Energy requirements = 75 kW
 Water requirements = 50,000 (olives/day) \times 0.002(m³/kg) = 100 m³/day
 Cellar tanks size = 50,000 l/unit
 Number of cellar tanks = 576,086 (l)/50,000 (l/Units) = 12 tanks
- iv) Investment for plot, access, fence, transformer, etc.
 Plot - $10,000 \text{ m}^2 \times 5.2$ (\$/m²) = \$52,000
 Access = \$25,800
 Transformer - 150 kVA = \$38,700
 Other Investments - = \$13,000
 Total = \$129,500
- v) Investments for the reception area:
 Buildings and facilities (plumbing, wiring, sewers, etc.)
 $250 \text{ (m}^2) \times 387$ (\$/m²) = \$96,750
 Machinery (cleaning, washing, weighting, transport and storage) = \$193,548
 Total = \$290,298
 Workforce = 2 shifts \times 2 workers = 4 workers
- vi) Investments for the processing area:
 Building and facilities (plumbing, wiring, sewers, etc.)
 $300 \text{ (m}^2) \times 645$ (\$/m²) = \$193,500
 Processing machinery = \$322,600
 Total = \$516,100
 Workforce = 3 shifts \times 2 workers = 6 workers
- vii) Investments for the storage area:
 Building and facilities (plumbing, wiring, sewers, etc.)
 $240 \text{ (m}^2) \times 323$ (\$/m²) = \$77,520
 Stainless steel tanks (50,000 l/unit) -
 $12 \text{ (tanks)} \times 4830$ (\$/unit) . . . = \$58,068
 Total = \$135,588
 Workforce = 1 shift \times 1 worker = 1 worker
- viii) Investments for the "By product" area:
 Building and facilities (plumbing, wiring, sewers, etc.)
 $150 \text{ (m}^2) \times 258$ (\$/m²) = \$38,700
 Workforce = 0

- ix) Investments for laboratory and offices:
 Building and facilities (plumbing, wiring, sewers, etc.)
 $100 \text{ (m}^2\text{)} \times 516 \text{ (\$/m}^2\text{)} \dots\dots = \$51,600$
 Workforce = 1 shift \times 3 employees = 3 employees
- x) Investments Summary:
- | | |
|----------------------------------|-------------------|
| Plot, access, fence, transformer | = \$129,500 |
| Reception area | = \$290,298 |
| Processing area | = \$516,100 |
| Storage area | = \$135,588 |
| By products area | = \$38,700 |
| Laboratory, offices | = <u>\$51,600</u> |
| Total | = \$1,161,786 |
- xi) Workforce Summary:
- | | |
|----------------------------------|---------------|
| Plot, access, fence, transformer | = 0 |
| Reception area | = 4 Workers |
| Processing area | = 6 Workers |
| Storage area | = 1 Worker |
| By products area | = 0 |
| Laboratory, offices | = 3 Employees |

Therefore the workforce required is eleven workers during the processing season and three employees all the year.

References

1. Civantos, L., R. Contreras, and R. Grana. 1992. Obtención del aceite de oliva virgen [Virgin olive oil extraction]. Madrid: Ed. Agrícola Española.
2. FUENTES CARDONA S. A. Ubeda - Jaen (Spain)
3. HURAL S. A. (Spain)
4. PIERALISI, S. A. Zaragoza (Spain)
5. García-Vaquero, E., and F. Ayuga, 1993. Diseño y construcción de industrias agroalimentarias (Agrofood industries design and construction) Ed. Mundi Prensa S. A. pp. 438 Madrid .

4.3 Coffee Drying

Pedro Amorim Berbert and Juarez de Sousa e Silva

Coffee is a unique agricultural commodity. Because of the many successive layers enclosing the seed, its drying characteristics are different from those of other agricultural products such as cereals and oilseeds. The outermost layer of a ripe coffee cherry is a thin pericarp or skin, which covers the pulp or fibrous fruit flesh. Next there is a layer of mucilage, approximately 0.8-mm thick, which is translucent and colorless. The mucilage has no definite cellular structure and resembles an amorphous gel. Then, there is a thin yellowish parchment layer or endocarp and, finally, a silver skin covering the green coffee seed [1]. Thus, the processes involving heat and mass transfer are different in coffee in

the whole-fruit form than in other crops like wheat, soybeans, and maize, which have remarkably different seed structures.

4.3.1 Natural Coffee

The factors that must be taken into account when deciding the method that shall be used to harvest and dry coffee are determined mainly by economics, climate, and rainfall distribution. In large areas of Brazil, a long dry and warm period usually coincides with the harvest season. This induces a very rapid passage from the ripe to the partially dry stage, thus making it impossible to harvest a large portion as fresh ripe fruit. Cherries that are overripe and dried to the point of 45% (w.b.) moisture content or less cannot be pulped because the skin is hard. Consequently, it is necessary under these conditions to dry the cherries as whole fruits, producing what is referred to as *natural* coffee [2].

4.3.2 Washed Coffee

The drying of washed coffee is another drying method that should be considered by producers who are contemplating opportunities to deliver a high-quality product to coffee processors. To prepare washed coffee, strip-picked cherries in various stages of ripeness are subjected to water flotation to separate ripe cherries, which sink, from green and partially dried fruits, which float. Next, the ripe-fruit portion is squeezed in a pulping machine, which removes most of the skin and pulp leaving a slippery layer of mucilage. Because this cannot be readily dispersed in water, it is removed by natural fermentation or fermentation with added enzymes. The product is called *washed* coffee because the dispersible fermented mucilage finally is removed by washing with water. After draining off the excess water, the coffee is dried to about 13% (w.b.) moisture either in high-temperature mechanical or fixed-bed dryers or under the sun on paved drying terraces. Carefully prepared and handled washed coffee is generally clean in flavor and free from undesirable elements, but it lacks in body or full-flavored richness compared with well-prepared natural coffee [1].

4.3.3 Pulped Coffee

Somewhat different from the method of preparing washed coffee is the processing method used to obtain *pulped* coffee. In this method, both pulping and partial removal of mucilage are accomplished in a single operation, and the coffee subsequently is spread on sun-drying terraces. The incomplete removal of mucilage increases the difficulty of drying for the first day or two because the seeds become very sticky and viscous, rendering the coffee hard to handle; then, if favorable weather prevails, the surface becomes dry and the coffee may be handled in the usual way thereafter [1].

4.3.4 Coffee Quality

Good control of coffee quality is related to the time it has been exposed to high temperatures during drying. As an approximate guide, coffee will tolerate temperatures of 40°C for a day or two, 50°C for a few hours, and 60°C for less than an hour without damage. If these temperature–time limits are exceeded, damage to coffee quality may

be expected because overheating during drying produces sour or cooked flavors in the brewed coffee [2]. Nonetheless, Castro [3] observed that, compared with the sun-drying procedure, the quality of the brew was not impaired when natural and washed coffee were dried at 80°C in a 0.5-m-deep fixed-bed dryer with a 3-hour stirring interval and an airflow rate of $12 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$.

Final moisture-content uniformity is one of the most important parameters defining coffee quality. In cases in which drying is carried too far in order to achieve the set final mean moisture content, bean moistures lower than 10% (w.b.) can result with marked loss in coffee quality. Upon storage, even if coffee beans reestablish their equilibrium moisture with the ambient air, the harm done to the coffee quality will not be corrected [2].

4.3.5 Coffee-Drying Methods

Due to their high moisture content at harvest, 60% to 70% (w.b.), ripe coffee cherries do not flow easily in handling equipment (gravity spouts, hoppers, bucket elevators, augers) and conventional mechanical dryers. Drum-type rotary dryers are an alternative, but they generally are criticized for having low efficiency. As a result of this, the typical coffee-drying process in Brazil consists of two different drying stages. In the first stage, freshly harvested whole coffee cherries are spread on paved terraces, where they are allowed to dry under the sun until they reach 35% to 30% moisture (w.b.), in the second stage the coffee is dried in high-temperature mechanical or fixed-bed dryers down to about 13% (w.b.) If the climate is such that dependable sunshine is available during the harvest season, the drying process may be conducted entirely in open air. In this case, the cherries are spread out on the drying terrace after harvesting and dried to about 13% (w.b.) in a single operation. Another alternative is the complete drying of whole coffee cherries in fixed-bed dryers. The principal drawbacks in utilizing mechanical dryers have been the fact that they are designed to dry other products than coffee, and their relative high cost. Despite the recent efforts to change this situation most of the commercially available dryers still are inefficient and thus far have been used mainly in large-scale operations.

Some innovative grain-drying methods generally applied to cereals and oilseeds have been introduced in coffee-drying facilities in the past few years in an effort to increase the drying capacity and the energy efficiency of conventional coffee-drying installations, and at the same time to maintain coffee quality. These methods include dryeration, reversed-direction airflow drying, and combination drying. Several other high-temperature, continuous-flow drying systems that traditionally have been used in either the United States or Europe to dry cereal grains to safe moisture levels for long storage periods have been adapted to dry natural, washed, and pulped coffee. These methods include cross-flow, concurrent-flow, counterflow, and mixed-flow drying.

Sun Drying

Freshly harvested natural coffee generally has a wide range of moisture contents (70%–25% [w.b.]). On arrival at the drying facility the coffee is subjected to water flotation to separate soft ripe cherries from green and partially dried hard cherries. These two groups are spread out in separate parts on the drying terrace using hand

carts perforated for water drainage and equipped with a door located in the bottom. The door is opened as the car is puled along leaving a layer of coffee of regular thickness on the surface of the terrace.

The thickness of the coffee layer is approximately 4 cm at the beginning of the drying process and may be increased to 10 cm when the coffee approaches the final moisture content. During the daytime drying period the coffee frequently is stirred using rake-like tools pushed by hand.

In the late afternoon of the fourth or fifth day of drying, when the moisture content has dropped to approximately 30% (w.b.), the coffee is gathered into heaps or piles oriented along the highest slope of the terrace and covered with plastic sheets or tarpaulins. The sun's heat absorbed during the day is partially conserved during the night allowing a better moisture distribution within the cherries. The heaps or piles are uncovered later in the morning and removed from the previous position to allow the wet surface of the terrace to dry. The coffee is spread on the terrace again and the operations just described are repeated until the coffee reaches the desired level of moisture. The sun drying of washed coffee follows procedures similar to those used in the drying of natural coffee. The main difference is that washed pulped coffee has a very uniform initial moisture content and requires about one third of the drying time required for natural or whole-fruit coffee [1].

In a drying experiment conducted by Lacerda Filho [4], the efficiencies of drying terraces constructed of different materials (brick, concrete, asphalt, and hard soil) were determined and the coffee quality also was evaluated. Table 4.1 shows the results of the experiment carried out to dry natural coffee with 62% (w.b.) initial moisture content. All treatments were subjected to the same solar drying conditions. The product subjected to sun drying on compacted-soil terraces resulted in coffee of poor quality compared with that dried on brick, concrete, and asphalt terraces.

Fixed-bed Drying

For small-scale operations, drying coffee in fixed beds has become one of the most widely used techniques. Strip-picked coffee with a wide range of initial moisture contents is placed in the dryer, and heated air is passed up through the coffee using a power-driven fan. Loading and unloading generally are done by hand. Traditionally, as in cross-flow dryers, the air temperature must be kept at moderate levels ($<50^{\circ}\text{C}$) in order to minimize

Table 4.1. Types of terrace drying of natural coffee

Type of Sun-Drying Terrace	Moisture Content after 16 Days (% w.b.)	Specific Energy Requirement ($\text{kJ}\cdot\text{kg}^{-1}$)
Hard soil	18.0	17,870
Brick	14.2	16,600
Concrete	13.3	16,970
Asphalt	11.3	15,900

Source: [4].

overdrying in those layers close to the input-air side of the dryer. Generally, the drying is halted when the average moisture content of the whole bed has reached the required level for safe storage. At this time, the grain close to the exhaust air side of the dryer still is underdried [5].

Even though exposing the operator to harsh conditions of air temperature and humidity, stirring the coffee manually is still a common practice adopted to break up the drying zone and obtain a more uniformly dried product. So far very little research on coffee-stirring devices has been done to determine the extent of mechanical damage to the product. However, the introduction of stirring augers increases both the fixed and operating costs of the dryer.

Silva and Lacerda Filho [6] designed and built a fixed-bed dryer to dry natural, washed, and pulped coffee. The dryer has been widely adopted by small- and medium-scale farmers and has been used to dry other agricultural products such as beans and corn. The dryer is 5.0 m in diameter and is comprised of a 0.6 m-high plenum chamber and drying section resulting in a total height of 1.2 m. The walls consist of one brick layer 0.15 m thick covered with plastering on both surfaces. Production of heat takes place in one stage in a downdraft direct-combustion furnace using wood or coal as a fuel source. The inside of the furnace is lined with insulating firebricks, and a paste of sand, molasses, and soil is plastered on to the exposed surfaces of the furnace wall.

The system is equipped with a cyclone chamber in which the ash is trapped and natural air is blended with the flue gases to obtain the proper drying air temperature. The cyclone chamber is made of brick and consists of a cylinder having height and diameter of 1.2 and 1.0 m, respectively. The blended gases are drawn through the same backward-curved centrifugal fan used to force air through the bed of coffee.

Drying runs have consistently shown that the fixed-bed dryer is capable of reducing the moisture content of a 0.4 m-high layer of natural coffee from 60% to 12% (w.b.) in 32 hours, provided the drying air temperature is kept at 55°C and the coffee bed is stirred in intervals of 2 hours.

The amount of energy (6630 kJ·kg⁻¹) consumed during the drying of a 0.5 m-deep natural-coffee bed is approximately 65% higher than the amount consumed during the drying of washed coffee [3]. These values were obtained for coffee originally at 52% (w.b.) and subsequently dried to about 14% (w.b.) with an airflow rate of 12 m³·min⁻¹·m⁻², drying-air temperature of 60°C, and a stirring interval of 3 hours. Dryer output increases from 9.8 (natural coffee) to 18.7 kg·h⁻¹·m⁻² (washed coffee) for those same drying conditions.

Counterflow Drying

Silva [7] described the performance of an intermittent single-stage counterflow dryer used in drying natural coffee from 30% down to 12% moisture. Table 4.2 summarizes the performance evaluation of the dryer using an airflow rate of 18.5 m³·min⁻¹·m⁻² and drying air temperatures of 60, 80, and 100°C. Notwithstanding the use of considerably higher drying-air temperatures compared with those normally used in conventional fixed-bed dryers, no quality deterioration was observed in the coffee after drying and roasting.

Table 4.2. Effect of drying-air temperature on counterflow drying of natural coffee

Drying-air Temperature (°C)	Total Drying Time (h)	Specific Energy Requirement (kJ·kg ⁻¹)	Throughput (dry kg·h ⁻¹)
60	21.5	8300	50.2
80	14.2	7550	76.1
100	10.2	6440	105.9

Source: [7].

Concurrent-flow Drying

Osório [8] reported on a recirculating batch single-stage concurrent-flow dryer that will dry natural coffee from an initial moisture content of 25% to 11% (w.b.) in 7.5, 6.0, and 5.0 hours for drying air temperatures of 80, 100, and 120°C, with specific energy requirements of 5700, 4870, and 4760 kJ·kg⁻¹, respectively. The dryer has an effective height of 4.0 m, is capable of holding approximately 2300 kg of coffee at 25% (w.b.) moisture content, and operates with an airflow rate of 27 m³·min⁻¹·m⁻². The grain flows by gravity from a 1.5 m–deep holding bin and enters a 0.7 m–deep drying chamber and then a tempering section 1.8 m high. The discharge auger located at the bottom of the dryer guarantees a coffee velocity of 3.5 m·h⁻¹, so that the retention time of the coffee in the drying section is 0.2 h. The unloading device removes partially dried coffee from the tempering zone and conveys it back to the holding bin at the top of the dryer. Even though higher temperatures than those found in conventional fixed-bed dryers were used, no quality deterioration in the coffee brew was observed. It must be remembered that due to the evaporative cooling effect at the inlet of the drying chamber, the coffee does not reach the drying-air temperature.

In an effort to reduce specific energy requirements and improve the efficiency during the drying of natural coffee, Pinto [9] proposed a new dryer design that combines the counterflow and concurrent-flow drying methods, in separate stages, in one single dryer. The drying-air inlet is located halfway down the coffee column. Drying in the first stage is accomplished using the counterflow-drying concept, and then the coffee flows directly to the second stage, where it is dried as in a concurrent-flow dryer. The dryer is fitted with a 60-degree gravity hopper, which delivers the coffee to a central point below the tempering section, from whence it is augered to an elevator pit. The length of both the counterflow and concurrent-flow drying sections is 1.1 m, and the dryer is capable of holding 4500 kg of natural coffee at 30% (w.b.) moisture. Coffee velocity inside the dryer is 1.44 m·h⁻¹, so that it takes approximately 0.8 hours for the coffee to pass through each drying section in each drying pass.

Table 4.3 shows the results of a performance evaluation conducted with an experimental counterflow–concurrent flow dryer using drying-air temperatures of 80, 100, and 120°C, and an airflow rate of 20 m³·min⁻¹·m⁻². The throughput (kg·h⁻¹) is based on a 30% to 12% (w.b.) moisture reduction. A comparison of the results presented in Table 4.3 shows that total drying time and the specific energy requirement decrease 44% and 6.4%, respectively; the drying capacity increases 80% if the temperature is increased from 80 to 120°C.

Table 4.3. Effect of temperature on drying coffee in an intermittent two-stage experimental counterflow–concurrent flow dryer

Drying-air Temperature (°C)	Total Drying Time (h)	Specific Energy Requirement (kJ·kg ⁻¹)	Throughput (dry kg·h ⁻¹)
80	22.5	6070	200
100	15.7	5660	290
120	12.6	5680	360

Source: [9].

Dryeration

The dryeration process, a grain-drying method that involves both high-temperature drying and aeration of the product, is one of the innovative drying methods that has been adapted to coffee drying systems. In using the dryeration process, the moisture content of the coffee exiting the dryer is approximately 2% higher than the desired level for safe storage. The hot coffee is conveyed to a holding bin, where it is allowed to temper with no airflow for no less than 4 hours. Then the coffee is transferred to another bin, where it is cooled with low airflow rates. During the aeration or cooling some drying takes place and the remaining 2% of moisture is removed. Dryeration provide three advantages over traditional coffee drying methods: increased dryer capacity, reduced energy requirement, and better coffee quality [10–12].

The effects of drying-air temperature and tempering or steeping period on the moisture difference throughout a fixed bed of natural coffee and the energy requirement during the dryeration process already have been determined [13]. Table 4.4 summarizes the mean values of final moisture content difference throughout a 0.4 m–deep coffee bed for three drying-air temperatures (50, 60, and 70°C), one airflow rate (15 m³·min⁻¹·m⁻²), and three tempering periods (0, 6, and 12 hours). The values presented in Table 4.4 were obtained using natural coffee with 28% (w.b.) initial moisture content; the high-temperature drying was interrupted when the moisture content of the coffee beans reached 13% (w.b.), and 2% of moisture had been removed during aeration or cooling.

Table 4.4. Final percentage moisture-content difference (w.b.) obtained during the dryeration of a 0.4 m–deep fixed-bed of natural coffee

Temperature	Tempering Period		
	0 h	6 h	12 h
50°C	3.2	2.3	1.7
60°C	3.6	3.0	2.8
70°C	3.8	3.0	2.9

Source: [13].

Note: Coffee harvested at 28% (w.b.) and dried to 11% (w.b.) with an airflow rate of 15 m³·min⁻¹·m⁻².

From the values presented in Table 4.4, it can be concluded that a drying-air temperature of 50°C and 12 hours of tempering is the best dryeration treatment for natural coffee, for it results in a final moisture difference of 1.7%, almost 50% less than the difference obtained with the conventional drying method.

It is appreciated that an airflow rate of $15 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$ significantly exceeds the values normally encountered in grain dryeration processes. However, coffee-storage bins generally are not equipped with perforated floors. Thus the aim is to use the fixed-bed dryer as a tempering bin, so that the fixed costs are reduced by using the same fan for both high-temperature drying and aeration.

Reversed-direction Air-Flow Drying

Reversing the airflow direction at regular intervals throughout the drying period of coffee in a fixed bed is another method that has been proposed in an effort to achieve even drying and, by minimizing the moisture difference throughout the bed depth, obtain a product of better final quality. Using this method the difference between the maximum and minimum moisture contents in the coffee can be greatly reduced as compared with the conventional drying method. As a shortcoming, the drying efficiency is slightly lower for the reversed airflow dryer.

The concept of reversing airflow direction at regular intervals during drying of parchment coffee was introduced as early as 1952 by Fukunaga and Strohmman, cited by Kinch [14], but no serious attempts were made then to analyze the influence of the several drying parameters on final moisture-content difference and overall drying rate. It was only recently that a comprehensive study of the reversed-direction airflow drying method has been carried out and successfully applied to the drying of natural coffee [15].

Tables 4.5 and 4.6 summarize simulated performance evaluations of reversed-direction airflow drying versus conventional one-direction airflow drying for drying-air temperatures of 50°C and 70°C, respectively. The mean ambient air temperature and relative humidity used as input data for the simulation model were 15.8°C and 82.0%, respectively. As for the product, the average conditions used as input data were 25% (w.b.) initial moisture content, 13% (w.b.) final moisture content, and 15.8°C initial temperature. Simulations were conducted using three reversing-time intervals, 3, 4, and 6 hours, and an airflow rate of $15 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$. This procedure aimed at analyzing the effect of reversing-time interval, at each temperature, on the specific energy requirement and total drying time and identifying the set of conditions that would result in the most uniform moisture-content profile throughout a 0.90 m-deep coffee bed. Comparative simulations were performed using the conventional drying method. The uniformity index presented in these tables is defined as the percentage of grain in the bed that contains moisture within the range $13\% \pm 0.5\%$ (w.b.).

The values shown in Tables 4.5 and 4.6 show that for the same drying temperature, the specific energy requirement decreases with increasing reversing-time interval. Nonetheless, from an engineering point of view the increase in specific energy requirement associated with the reversed-direction airflow drying method was considered to be negligible for all cases studied.

Table 4.5. Average drying parameters of the reversed-direction airflow drying method versus the conventional one-direction airflow method at 50°C

	One-direction Airflow	Reversed-direction Airflow		
		3-h Reversal Interval	4-h Reversal Interval	6-h Reversal Interval
Specific energy requirement (kJ·kg ⁻¹)	9150	9438	9360	9286
Total drying time (h)	12.7	13.1	13.0	12.9
Final moisture-content difference (% w.b.)	3.1	0.9	1.2	1.0
Uniformity index (%)	33	100	83	100

Source: [15].

Table 4.6. Average drying parameters of the reversed-direction airflow drying method versus the conventional one-direction airflow method at 70°C

	One-direction Airflow	Reversed-direction Airflow		
		3-h Reversal Interval	4-h Reversal Interval	6-h Reversal Interval
Specific energy requirement (kJ·kg ⁻¹)	7147	7408	7282	7166
Total drying time (h)	6.2	6.5	6.4	6.3
Final moisture content difference (% w.b.)	5.4	1.8	2.5	5.2
Uniformity index (%)	33	84	50	33

Source: [15].

From the experimental and simulated results obtained thus far it is evident that the reversed-direction airflow drying method is very effective in promoting a marked reduction in the final moisture-content difference throughout the coffee bed as compared with the conventional drying method. Reductions in final moisture-content difference ranging from 60% to 70% generally are observed by reversing the airflow direction for a drying-air temperature of 50°C, as compared with the conventional drying method. For the latter method, increasing the temperature had no effect on the uniformity index. Nonetheless, the final moisture-content difference increased considerably as higher drying air temperatures were used. For 70°C, reversing the airflow direction every 3 hours resulted in a higher uniformity index and a lower final moisture-content difference compared with the conventional drying method. Despite the reduction of 67% in the final moisture-content difference as compared with the conventional drying method, the nonuniformity of the moisture distribution still may jeopardize the quality of the product after roasting. If the beans are not thoroughly mixed after drying or if they are not allowed to equalize their moisture content, beans with higher moisture content probably will not pyrolyze, and the overdried ones will scorch during roasting. The result will be an unpalatable product. For

a drying air temperature of 70°C, reversing the airflow every 6 hours has no significant effect on the reduction of the final moisture difference, for the reversion occurs almost at the end of the drying period.

Lower drying air temperatures, up to 50°C, are considered to be more suitable for drying coffee in fixed beds by reversing the airflow direction either at 3- or 6-hour intervals. Periodic airflow reversal also prevents the build-up of harmful condensation in the top layers of the coffee bed.

In comparing this drying method with other techniques proposed to reduce the final moisture distribution throughout the bed, it is considered that reversing the airflow direction at regular intervals can be easily implemented in both cross-flow and fixed-bed coffee dryers with minimum design changes and comparatively low additional costs.

Combination High-temperature Ambient-air Drying

Combination drying is one of the latest concepts in coffee-drying technology. It is the drying method in which both high-temperature processes and natural-air or low-temperature drying procedures are combined in an attempt to provide a high-quality product as compared with using only high-temperature drying [11]. The high-temperature drying stage is used to reduce coffee moisture contents from approximately 60% to 25% (w.b.) or less, so that natural air drying can be used successfully to complement the drying by further reducing the moisture content of the product to safe limits.

Unlike the dryeration process, in combination drying the hot coffee is transferred directly to the storage bin where the remaining moisture will be removed using ambient air or low temperature. In combination drying coffee is dried in the high-temperature dryer to a moisture level ten to twelve percentage points above the value for a safe storage, with the result that the recommended minimum airflow rates for the aeration stage in combination drying are 15 to 25 times more than the maximum airflow rate used in the cooling stage of the dryeration process [16].

Combination drying provides three advantages over typical high-temperature high-speed drying: increased drying capacity, reduced fuel requirement, and better coffee quality through reducing the final moisture difference throughout the coffee bed. As compared with the dryeration process, the main advantage of combination drying is the elimination of the extra handling step associated with the tempering bin. The main disadvantage of combination drying is the requirement of a relatively high level of capital investment and management in cases in which it is purchased as a unit because two complete drying systems are included [11, 12, 17].

The usual procedure to dry natural coffee on the farm using the combination method is as follows: Ripe cherries that have been strip-picked at moisture contents ranging from 50% to 65% (w.b.) are separated from the rest by water flotation and screening and then dried in either two or three separate stages. Where three stages are used, the coffee is first dried on paved sun-drying terraces until it reaches approximately 35% (w.b.) Then, the partially dried fruits are conveyed to a high-temperature dryer, where their moisture content is further reduced to about 25% (w.b.) In the third stage the coffee is bin-dried to approximately 13% (w.b.) moisture using natural air. In using two stages, the sun-drying procedure is eliminated and the moisture content at harvest is reduced to approximately

25% (w.b.) using the high-temperature dryer alone. Combination drying also is applied to the drying of washed and pulped coffee, whereby the product is delivered directly to the low-temperature drying bin after the sun-drying procedure or the high-temperature drying method.

The natural-air drying stage in combination drying has recommended airflow rates in the (1:1 to 1:1/2) of the airflow range normally used in the high-temperature drying stage [12]. So airflow rates varying in the range from 7 to 15 m³ · min⁻¹ · m⁻² generally are used. This is enough air to dry relatively wet coffee as a result of the drying capability of the natural air. The fan should be started as soon as the first lot of coffee is delivered to the bin and switched off during periods of adverse drying weather or when the mean moisture content of the coffee in the surface layer of the bed reaches the target moisture content. For natural-air drying systems, the total drying time depends on the initial moisture content and climatic conditions.

Attempts to use high initial moisture content natural coffee in the low-temperature stage of combination drying thus far have been unsuccessful [18]. For example, experimental drying runs have shown that due to high initial moisture contents, 27% to 30% (w.b.), excessive heating developed within the coffee bed after approximately 10 days of fair weather conditions (0.0124 kg·kg⁻¹ humidity ratio and temperature of 18°C), and careful inspections generally indicated invasion by fungi. In cases in which the drying was not interrupted it was observed that the ambient air was not generally cool enough to serve as a deterrent to fungi development, and a strong musty odor generally developed. The results obtained thus far suggest that drying high-moisture natural coffee in the low-temperature stage of combination drying is a very hazardous procedure. However, sufficient data are not yet available to condemn it as impossible. It can be reasoned that better drying weather or the use of higher airflow rates might prove satisfactory in reducing the moisture content of relatively wet coffee to a level safe enough to prevent fungi development, but the risks involved would still be high. Another alternative would be the reduction of coffee-bed depth.

On the other hand, drying tests using high-moisture pulped coffee have been run successfully [18]. It takes approximately 1050 hours to dry coffee initially at 37% (w.b.) to a mean moisture content of 13% (w.b.), a moisture extraction of 24 percentage points. The results obtained implies an average moisture extraction rate approximately four times greater than that obtained with natural coffee, from which it can be seen that the low-temperature drying of pulped coffee is considerably more efficient than that of natural coffee.

Obtaining accurate knowledge of the temperature within the bed during natural-air drying of relatively wet coffee is essential to identify hot spots and to avoid spoilage reaching an advanced stage in portions or in the whole bulk. Increases as high as 10°C above ambient temperature have been observed within the coffee bed as a result of mold growth. When this happens, ambient-air temperature generally is below the temperature within the coffee bed during the whole drying period, indicating high rates of respiration and that fungi are already present at the early stages of the process.

The mixing of different lots of coffee of markedly different moisture contents, a common practice from the farm to the final product processor, should be avoided whenever

possible. All tests carried out using mixed lots of coffee with different moisture contents resulted in brews of poor cupping quality. It is believed that only when all coffee actually has the same or similar moisture content prior to the mixing will it produce a brew with full flavor development.

It is expected that one or a number of bad weather days will not adversely affect the efficiency of low-temperature drying systems. Stopping the fan and waiting for more favorable weather fails to recognize that the first and foremost requirement in ambient-air drying is to keep the grain cool and prevent heating [17]. However, it is a matter of common knowledge that keeping coffee at moisture contents over 15% (w.b.) for long periods of low-temperature drying or storage is unsafe because mold and, consequently, cup-quality deterioration may occur. But rewetting of dried coffee as a result of continuous fan operation during periods of adverse weather is also a hazardous procedure because the beans may become pale and bleached out in appearance, signifying aroma and flavor deterioration. So unlimited fan operation during poor drying weather conditions may be recommended as long as the moisture content of coffee is above approximately 17% (w.b.)

In conclusion, combination drying of coffee offers a reliable alternative to farmers who wish to deliver a high-quality product to coffee processors. However, its success depends on good design, proper sizing and well-coordinated operation and management of the natural-air drying fan. Under appropriate weather conditions it is feasible to dry natural coffee from approximately 25% down to 13% (w.b.) using an airflow rate of $8 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$ without providing significant supplemental heat to the drying air. However, the drying of natural coffee with moisture contents above 26% (w.b.) is a very hazardous procedure and should not be recommended under poor weather conditions. On the other hand, studies [18] have shown that the natural-air drying stage is very effective to dry pulped coffee fairly high in moisture (37% w.b.) to a safe storage level.

4.3.6 Coffee Storage

Green coffee in producing countries traditionally is stored in bags rather than in bulk. Pallet storage of bagged green coffee allows the segregation of lots, a very important aspect considering that the product is priced according to cup flavor. Besides such considerations as accessibility to small lots, normal air circulation about the bags, easy inspection, and sampling are important factors to consider. Bagged coffee usually is stored in warehouses where 60-kg bags are piled, forming stacks, generally with little or no control of the environmental conditions. In spite of this, it is possible to maintain the product stored for relatively long periods (up to 5 years) without deterioration as compared with cereals such as corn or wheat. Inside the warehouse, provision is made for aisle space along walls for inspection and aisle space between stacks (3.8 m) for moving the product with forklift trucks. According to Sivetz and Foote [1] only two thirds to three quarters of the floor area is generally available for storage. The main disadvantages of bagged storage of green coffee relate to the requirement of intensive labor, the cost of bags, and difficulties associated with insect control. Discoloration of the product and reduction in bulk density are other problems related to the traditional

method of storing coffee in bags. Prices can suffer reductions of up to 40% according to the level of damage during storage. Finally, the following additional aspect should be considered during pallet storage of bagged coffee: The amount of light reaching the bags must be controlled carefully, for under a bright environment the beans may become pale and bleached out in appearance, signifying aroma and flavor deterioration.

Although not widespread in the producing countries, bulk storage of green coffee is a procedure that should be considered by producers or firms handling large quantities of relatively uniform beans. Bulking large quantities facilitates processing operations such as blending and roasting. Nowadays, bulk storage of green coffee is restricted to producers who are able to deliver only less than a few hundred bags to coffee processors and is usually carried out in wood frame constructions. Long-term storage requires both a forced-air circulation system to maintain grain equilibrium moisture content and a temperature monitoring system to detect hot spots before extensive damage occurs. An objection to in-bin bulk storage of green coffee is that accurate inventories are difficult to maintain as the level of beans is not even and the quantity assessed by visual estimate can be quite a few bags in error [1]. Accurate inventories of the amount of product in storage are essential because coffee is considerably more expensive than cereal grains. The main advantage of bulk storage of green coffee is that the mechanization of the process allows a reduction of the labor required for handling the product as compared with the traditional method.

As stated previously, bulk storage of coffee is not a common practice in producing countries. Indeed, information available in the literature on bulk storage of coffee is still meager. Jordão *et al.* [19] compared the bulk storage of green coffee beans with the traditional method, by which coffee is stored in bags. Average moisture content of green coffee beans decreased from 10.4% to 9.6% (w.b.) after 5 years of storage in a metal bin equipped with a natural ventilation system, in an environment in which the average temperature and relative humidity were 24°C and 70%, respectively. Moisture content of the product, for the same environmental conditions, remained practically constant at 11% (w.b.) (pallet storage of bagged coffee) and 10% (w.b.) (bulk storage without ventilation). The bulk density of the coffee stored in both ventilated and nonventilated bins was reduced from 650 to 610 kg·m⁻³ during the 5-year period, whereas for the product stored in bags the level of reduction was more pronounced (from 650 to 540 kg·m⁻³). Chemical analysis revealed that the green coffee suffered similar reactions under all three types of storage.

The color of the beans (bluish-green) did not alter during storage in bulk with natural ventilation. Nonetheless, some discoloration was observed in the beans stored in bags as well as in bulk storage without ventilation. The critical evaluation of coffee aroma and taste, that is, evaluation of cup quality or *cupping*, revealed that the three storage systems are capable of producing coffee that can be classified as *hard*. This denotes an astringent flavor, one that causes puckering and a bitter impression. A hard coffee does not have the full development of flavor and acidity characteristics of high-grown coffees but may have as much or more body. It has been concluded that it is feasible to store green coffee with moisture contents in the range from 10% to 11% (w.b.) in bulk for periods up to 3 years without quality loss.

Notation

Γ	angle of repose (degree)
Θ	grain temperature ($^{\circ}\text{C}$)
ψ	relative humidity ($0 \leq \phi \leq 1.0$)
ρ	bulk density ($\text{kg}\cdot\text{m}^{-3}$)
c_p	specific heat of coffee ($\text{kJ}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$)
h_{fg}	enthalpy of vaporization of water in coffee ($\text{kJ}\cdot\text{kg}^{-1}$)
M	moisture content of coffee (decimal dry basis)
MR	moisture ratio ($[M - M_e]/[M_0 - M_e]$)
T	air temperature ($^{\circ}\text{C}$)
T_{abs}	absolute air temperature (K)
t	time to dry to MR with drying-air temperature T_{abs} (h)

Suffixes:

e	equilibrium value
eq	equivalent
0	initial value

Appendix: Physical Properties***Thin-layer Drying Equation***

The following equation describes the drying rate of a thin layer of natural coffee at drying air temperatures ranging from 40 to 80 $^{\circ}\text{C}$ [20].

$$MR = \exp\left[-105.756 t_{eq}^{0.60564} e^{(-2751.51/T_{abs})}\right] \quad (4.A1)$$

Equilibrium Moisture Content

One of the main problems in previous attempts at setting up mathematical models to simulate coffee drying was the lack of a reliable equation for its equilibrium moisture content. Rossi and Roa [21] presented the following empirical relationship for the desorption isotherms for natural coffee:

$$M_e = (15272\varphi - 32478\varphi^2 + 33341\varphi^3) \exp[(-0.029458 - 0.0016309\varphi - 0.013695\varphi^2 + 0.0132050\varphi^3)T_{abs}] \quad (4.A2)$$

The resulting sigmoidal curve obtained from Eq. (4.A2) is too steep for relative humidities above 60% and does not fit well most of the experimental data found in literature. It is believed that many failures to validate coffee drying were due to the use of this equation to predict equilibrium moisture content. On the other hand, better overall accuracy is attained using the following empirical equilibrium moisture content equation proposed by Arteaga [20]:

$$M_e = 1.1282[-\ln(1 - \varphi_e)/(T_e + 40.535)]^{0.5405} \quad (4.A3)$$

Enthalpy of Vaporization

The absence of an accurate equilibrium moisture-content equation for coffee also led to inaccuracies in the development of equations for the enthalpy of vaporization of

moisture in coffee beans. The following equation was developed by Berbert and Queiroz [22] and was based on the method of correlating vapor pressure and latent heat data presented by Othmer [23]. It was developed using experimental data from Arteaga [20] in the 0.15 decimal d.b. to 0.25 decimal d.b. region.

$$h_{fg} = (2501 + 1.775\Theta)[1 + 1.872 \exp(-20.601M)] \quad (4.A4)$$

Specific Heat

The following equation developed by Villa and Roa [24] represents the specific heat of coffee at constant pressure.

$$c_p = 1.674 + 2.510[M/(1 + M)] \quad (4.A5)$$

Bulk Density

The effect of moisture content on bulk density of natural coffee is given by the following equation developed by Silva [7]:

$$\rho = (396.48 + 224M)/(1 + M) \quad (4.A6)$$

In a study conducted by Castro [3], the estimated bulk density of washed coffee as a function of moisture content was defined as in the following equation:

$$\rho = 371.78 + 255.17M \quad (4.A7)$$

Volume Reduction

The grain volume shrinkage generally is assumed to be negligible during simulation studies of the drying processes. This is based on the assumption that the decrease in bed height is not substantial for most cereal grains in continuous-flow dryers [10]. However, the assumption of negligible volume shrinkage for natural coffee during drying can impose serious limitations in simulation accuracy. Kinch [14] reported a pronounced reduction in the volume of parchment coffee during drying. Volume reduction of 24% was observed when drying from 55% to a final moisture content of 12% (w.b.). No correction for bed-height variation due to volume reduction is applied to the coffee-simulation models because to date no really comprehensive study describing the phenomenon for natural coffee has been undertaken.

Pressure Drop

Guimarães [18] observed that the pressure drop in experimental drying tests run with natural coffee was always smaller than 7.5 mm of water column per meter depth of coffee, whereas for pulped coffee this value was 10.0 mm H₂O per meter depth. Direct comparison of these results with published data is rather difficult because of differences in particle size, bed depth, porosity of the bed, and surface roughness. Also, the amount of reported data on the pressure drop through beds of coffee is meager. However, it is realized that a pressure drop of 7.5 mm of water column per meter depth of clean coffee is smaller than those values normally found in practice where foreign material will occupy some of the free space between the cherries, hence apparently compacting the bed and increasing the pressure drop. Afonso [25] made a series of measurements of pressure drop through beds of coffee. For a bed depth of 1.75 m and an airflow rate

of $10.0 \text{ m}^3 \cdot \text{min}^{-1} \cdot \text{m}^{-2}$, the pressure drops were 5.1 and 5.4 mm of water column per meter depth, for 23% and 14% (w.b.) moisture coffee, respectively.

Angle of Repose

The angle of repose of pulped coffee, variety Catuaí, containing 5% of foreign matter, as a function of moisture content ($0.12 \text{ d.b.} \leq M \leq 0.67 \text{ d.b.}$) at 20°C is given by the following equation ($r^2 = 0.98$):

$$\Gamma = -31.72M^2 + 39.30M + 36.06 \quad (4.A8)$$

The equation for the angle of repose as a function of moisture content ($0.11 \text{ d.b.} \leq M \leq 0.42 \text{ d.b.}$) obtained for the same product but without the presence of foreign matter is as follows ($r^2 = 0.99$):

$$\Gamma = -96.66M^2 + 70.65M + 28.54 \quad (4.A9)$$

References

1. Sivetz, M., and H. E. Foote. 1963. *Coffee Processing Technology, vol. I: Fruit—Green, Roast, and Soluble Coffee*. Westport, CT: AVI Publishing.
2. Sivetz, M., and N. W. Desrosier. 1979. *Coffee Technology*. Westport, CT: AVI Publishing.
3. Castro, L. H. 1991. Efeito do despolpamento, em secador de leito fixo sob alta temperatura, no consumo de energia e na qualidade do café (*Coffea arabica* L.) [Energy requirement during the drying of natural and washed coffee (*Coffea arabica* L.) in a high-temperature fixed-bed dryer]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.
4. Lacerda Filho, A. F. 1986. Avaliação de diferentes sistemas de secagem e suas influências na qualidade do café (*Coffea arabica* L.) [Assessment of several different drying systems and their effect on coffee quality (*Coffea arabica* L.)]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.
5. Paulsen, M. R., and T. L. Thompson. 1973. Effects of reversing airflow in a crossflow grain dryer. *Transactions of the American Society of Agricultural Engineers* 16:541–544.
6. Silva, J. S., and Lacerda Filho, A. F. 1984. Construção de secador para produtos agrícolas [Design and construction of a fixed bed dryer for agricultural products]. Informe técnico no. 41. Viçosa, Brazil: Conselho de Extensão da Universidade Federal de Viçosa.
7. Silva, L. C. 1991. Desenvolvimento e avaliação de um secador de café (*Coffea arabica* L.) intermitente de fluxos contra-correntes [Design and performance assessment of an intermittent counterflow dryer for coffee (*Coffea arabica* L.)]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.
8. Osório, A. G. S. 1982. Projeto e construção de um secador intermitente de fluxo concorrente e sua avaliação na secagem de café [Design and construction of a recirculating-batch single-stage concurrent-flow dryer for natural coffee]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.

9. Pinto, F. A. C. 1993. Projeto de um secador de fluxos contracorrentes/concorrentes e análise de seu desempenho na secagem de café (*Coffea arabica* L.) [Design and performance evaluation of a counterflow-concurrent flow dryer for natural coffee (*Coffea arabica* L.)]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.
10. Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1974. *Drying Cereal Grains*. Westport, CT: AVI Publishing.
11. Loewer, O. J., T. C. Bridges, and R. A. Bucklin. 1994. On-farm drying and storage systems. St. Joseph, MI: American Society of Agricultural Engineers.
12. Cloud, H. A., and R. V. Morey. 1980. Dryeration and in-storage cooling for corn drying. Agricultural Extension Service Report M-162. St. Paul, MN: University of Minnesota.
13. Cordeiro, J. A. B. 1982. Influência da temperatura e tempo de repouso na secagem de café (*Coffea arabica* L.) em camada fixa [Influence of temperature and tempering time on the drying of coffee (*Coffea arabica* L.) in fixed beds]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.
14. Kinch, D. M. 1967. Design criteria for mechanical drying of coffee beans. *Transactions of the American Society of Agricultural Engineers*, 10:40–42.
15. Berbert, P. A. 1991. Secagem de café (*Coffea arabica* L.), em camada fixa, com inversão de sentido de fluxo de ar [Drying of coffee (*Coffea arabica* L.) in a fixed bed with airflow reversal]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.
16. Navarro, S., and M. Calderon. 1982. Aeration of grain in subtropical climates. *Agricultural Services Bulletin* 52. Rome: FAO.
17. McKenzie, B. A. 1976. Operating grain dryers for capacity, fuel efficiency, and grain quality. West Lafayette, IN: Cooperative Extension Service, Purdue University.
18. Guimarães, A. C. 1995. Secagem de café (*Coffea arabica* L.) combinando sistemas em altas e baixas temperaturas [Combination drying of coffee (*Coffea arabica* L.)]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.
19. Jordão, B. A., R. S. Garrutti, E. Angelucci, I. S. Tango, and Y. Tosello. 1969/1970. Armazenamento de café beneficiado a granel, em silo com ventilação natural [Storage of green coffee in a bin with natural ventilation]. *Campinas, Coletânea do Instituto de Tecnologia de Alimentos* 3:253–281.
20. Arteaga, M. S. 1986. Modelación del proceso de secado [Modeling the drying process]. *Seminario de secado solar*, 2, 1986, Cusco, Peru, pp. 51–56. Lima: Instituto General de Investigación.
21. Rossi, S. I., and G. Roa. 1980. Secagem e armazenamento de produtos agropecuários com uso de energia solar e ar natural [Drying and storage of agricultural products using solar energy and air at ambient temperature]. Publicação ACIESP no. 22. Secretaria da Indústria, Comércio, Ciência e Tecnologia. Academia de Ciências do Estado de São Paulo, Brazil.
22. Berbert, P. A., and D. M. Queiroz. 1991. Método para determinação de uma equação para a entalpia de vaporização da água contida em grãos de café [A method to determine an equation for the enthalpy of vaporization of moisture in coffee]. *Engenharia Rural* 2(1):1–17.

23. Othmer, D. F. 1940. Correlating vapor pressure and latent heat data. *Industrial and Engineering Chemistry* 32:841–856.
24. Villa, L. G., and G. Roa. 1978. Simulação matemática de secagem de café e cacau. [Mathematical simulation of the drying of coffee and cocoa beans]. Campinas, Departamento de Engenharia Agrícola.
25. Afonso, A. D. L. 1994. Gradiente de pressão estática em camadas de frutos de café (*Coffea arabica* L.) com diferentes teores de umidade [Static pressure drop in fixed beds of coffee (*Coffea arabica* L.) as affected by coffee moisture content]. M.Sc. thesis, Universidade Federal de Viçosa, Brazil.

5 Effluent Treatment in Agroprocessing

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5.1 Effluents in Agroprocessing

P. Amirante

5.1.1 The Problem of Effluents

The protection of water from pollution is one of the aspects involved in the protection and conservation of the environment in which we live [1]. This problem, therefore, should be considered not only in terms of the introduction of harmful substances into the environment but also by means of analysis of human activity that can irreversibly modify the habitat, particularly causing pollution and changes in the vital means for life subsistence on the earth, air, water, and soil [2].

Nature, generally, has always found the way to restore environmental equilibrium; however, the industrial civilization and the development of large urban areas have caused an increase and concentration of pollution sources. Moreover, technical progress usually has resulted in an improvement in the standard of living that, added to population growth, has caused an increase in the waste to be disposed of [3].

Water-resource management thus implies reducing pollution and anything that causes alterations in the chemical, physical, or biological properties of water itself and sharply reduces its value as vital resource.

Within water-resource management, in particular, the development of industrial activities causes human pressure on land that has detrimental repercussions on the environment and on the productive activities related to it [4].

Among the industrial activities, the agroindustrial ones have particularly complex issues [1], including: the polluting load of mostly organic effluents with high suspended-solids content; the production of seasonal effluents related to the product to be processed; the quantitative and qualitative characteristics of the effluent that are not constant even in the short-run; and the low value added to the final product by the processing activity, which cannot cover the costs of effluent treatment and purification.

Nevertheless, in contrast with other industrial effluents, in those of agroprocessing both pathogens and heavy metals are absent. This means that even though the suspended or dissolved organic matter supplies a high polluting load according to the normal assessment parameters, it can be reused in agriculture as animal feed, after immediate

separation (flotation, sedimentation). If, however, it is in the final stage of treatment, by extracting biomass from sludge (centrifugation, drying, or composting) it can be used as an organic fertilizer.

The problem of effluent treatment, viewed within the framework of recovery and reuse, is, therefore, a serious environmental problem in both industrialized and developing countries. Each country, however, presents specific conditions in terms of technologies and technical development that make the characteristics of the problem extremely different. These aspects cause a great variability, within the same industry, that also is observed at a national level.

Actually, agroindustrial processing shows a natural adaptability to the local environmental conditions, including the characteristics of treated products, the climate, the land, the available resources, the socioeconomic scenario, and the presence of an agroindustrial or industrial system with which some production-related services can be shared [5].

Effluent treatment should involve consideration of the control of the processed products, the quantity of water utilized, the utilization of technologies for resource water saving, and reduction in the use of chemical detergents and disinfectants. These aspects are related to the management of the entire production process, which should be considered an integral part of effluent treatment [6].

The effluent treatment required to reduce or minimize the environmental impact entails a cost without any direct benefit to revenue. The treatment system, therefore, should have the following design characteristics: suitability for minimizing the polluting load to within the prescribed limits, environmental and technological sustainability; ease in management, and low investment and running costs [7].

5.1.2 Organic-Matter Cycle in Nature and Agriculture, and Effluent-Treatment Systems

In order to analyze the water-pollution mechanism one should start from different processing systems: they make use of raw materials, water, and air and, prior to processing, besides the final product gaseous, liquid, and solid waste may coexist.

Gaseous waste should be treated prior to being released into the atmosphere. Solid waste is a mass that may be easily contained and handled in the long term, whereas liquid waste usually is discharged into streams.

The working mechanism of polluting substances in a stream may be summarized as follows [1]: excessive oxygen consumption, release of toxic or harmful substances, and change in the water temperature. Pollution thus takes on different aspects according to whether it acts in flowing, stagnant, coastal, or ground waters.

In the case of agricultural and food industries, waste, generally, is characterized by a high organic biodegradable substance content. Such substances, in a stream, are transformed by microorganisms into more stable, nonpolluting, and low-energy substances.

If the process takes place in the presence of oxygen, organic substances are oxidized and the transformation releases energy that is used by aerobic microorganisms to grow and multiply themselves. If pollution consumes all the oxygen in the water, the anaerobic microorganisms use the oxygen contained in nitrates, sulphates, and phosphates and combine it with the carbon contained in organic matter, producing carbon dioxide.

When the oxygen in nitrates, sulphates, and phosphates is exhausted, the anaerobic bacteria combine carbon as well as the other elements directly with hydrogen, thus producing methane, hydrogen sulphide, and ammonium phosphate [1].

During transformation, these high-energy products release a lower amount of energy for the anaerobic microorganisms, which thus have a slower development than the aerobic ones. Therefore, whereas the aerobic processes produce quite stable substances and a humus that may even be used as biomass, the anaerobic processes produce combustible gases and other substances that may be harmful to the stream and should be appropriately reused and treated. Moreover, permanent anaerobic conditions might develop in the water, thus inhibiting the self-purification process.

Thus, considering the organic load concentration, effluents containing organic substances, generally, cannot be discharged freely into streams; they need to be treated to prevent the so-called permanent anaerobic condition that causes a stable state of pollution in the water [8].

In the choice of the treatment to be carried out, two priority conditions are necessary to influence the technological cycle of the processing industry directly: identification of the required water volume, so as to minimize wastage and the water volume to be treated, and the presence of recoverable substances in the effluent.

Although the need to save water is discussed in the subsequent analysis of each processing industry, it should be emphasized that if one takes the processing waste at the initial stage, different by-products including useful substances for human and animal nutrition can be extracted, such as proteins and fats.

It is clear that the issues behind the choice of a water-treatment system are numerous and not easy to solve. Besides the obvious need to review the processing cycle, and to reduce water and energy waste, the choice is whether to use traditional treatment techniques for effluents or to foresee new technology for the use and extraction of the organic by-products from water, treating effluents at the same time [9].

In order to use these technologies, careful experimental work should be carried out on a chemical-processing level to provide different solutions. Moreover, controls, with expert guidance on whether the resulting by-products are economically extractable, also should be carried out, taking into account the cost of the treatment plant as well.

On a preliminary basis it should be mentioned that the waste from productive establishments may be released into surface or deep streams, into the sea, onto soil and even used for agricultural purposes, or into public sewers. Whatever the outlet may be, effluents should be adapted to the acceptability limits prescribed by the legislation in force.

Water purification uses different methodologies, taking into account the type of discharge, the size and location of the plant, and the presence of municipal or centralized plants in loco.

Productive units may be equipped with single one treatment plants and may discharge treated water into streams; otherwise, if several similar productive units are present in the same area, they could install a centralized plant, with great technical and economic advantages.

The presence of a municipal urban wastewater-treatment plant would make it necessary to perform pretreatment alone, which is designed to remove the pollutants that

cannot be purified in the municipal plant or, in any case, to reduce the pollution rate to within the acceptable limits of the plant.

Based on this, it seems obvious that for small and medium sized agroindustries it is very difficult to have single treatment plants, and thus consortium plants would seem the most logical approach. Therefore, before making a detailed analysis of the different plants usable for each individual industry, it seems useful to briefly analyze the techniques most commonly applied in treatment plants [2].

A treatment facility consists of a combination of machines and equipment that, arranged in a preestablished sequence, is able to carry out some chemical, physical, chemical–physical and biological processes that can transform effluents according to the desired requirements.

Treatment usually includes pretreatment operations (or mechanical treatment), biological treatment, chemical treatment, physical treatment, and chemical–physical treatment.

Pretreatment Operations (Mechanical Treatment)

Mechanical treatment consists of removing those substances that may interfere with subsequent treatment from the water. It includes the following operations: screening, size reduction, removal of coarse materials, oil and fat separation, grinding, and primary settling.

Biological Treatment

Biological treatment is generally the central and main part of a system; it permits self-purification of water by means of either aerobic or anaerobic microorganisms.

These processes only act on biodegradable (naturally degradable through biological processes alone) substances and may be implemented through the following processes: filtration on percolating filters, activated sludge oxidation, or lagooning.

In the case of highly polluting waste and in energy-intensive industries (distillation of grape pomace or olive-oil extraction), anaerobic treatment plants may be proposed.

Chemical Treatment

Chemical treatment means the use of chemical reagents that act on some of the substances contained in water in order to:

- Oxidize or reduce some dangerous substances into nontoxic compounds (oxidation, reduction)
- Remove or eliminate the pathogens by chlorination, ozonation, and so on (disinfection)
- Reduce the pH to within the allowable limits for discharge (neutralization)
- Precipitate some pollutants dissolved in water as sludge, by means of chemical substances (precipitation)
- Use chemical reagents that eliminate repulsive electrical charges by acting on the small flocs formed during precipitation, thus favoring the formation of larger flakes or constituting chains that tend to link flakes with each other (coagulation or flocculation)

Physical Treatment

Physical treatment consists of water separation from coagulated or flocculated precipitates; it can be carried out

- By natural sedimentation with the constitution of a compact mass of jelly-like sludge (settling)
- By separation of the solid from the liquid particles, using a porous medium able to filter only liquid substances (filtration); this may be done both to remove the suspended solids in the liquids and to compact sludge
- By separation of the solid from the liquid particles through truncated rotors equipped with screw conveyors (centrifugation)

Chemical–Physical Treatment

With the improvement in purification techniques, other mixed chemical–physical treatment methods have enabled more advanced waste purification.

The most common ones include: ionic exchange, adsorption, flotation, stripping, evaporation, reverse osmosis and ultrafiltration.

Ionic Exchange

The ionic-exchange method consists of using substances (ionic-exchange resins) characterized by chemical structures that enable the polluting ions contained in water to be fixed by exchanging them with other nonpolluting ions.

Adsorption

Adsorption is a chemical–physical process by means of which polluting substances are retained on the surface of a finely ground solid, called *adsorbent*.

Among the adsorbing substances, the most common is activated carbon, which in some cases, after saturation, may be regenerated to reuse.

Flotation

Flotation is based on the principle that lower densities allow water-dissolved pollutants to be brought to the surface. Such a process also is favored for heavier substances contained in water, by means of tensioactive products and by air injection through diffusers located at the bases of containers.

Stripping

Stripping is a process that enables the elimination of either the gaseous substances dissolved in water or some substances that may be transformed into readily volatile products. The process usually occurs in a tower filled with porous inert material, where the water to be treated falls as a fine rain from above and air or vapors are injected from below to eliminate volatile substances from the liquid.

Evaporation

Evaporation is a process inverse to the processes normally used for purification: Water is separated by evaporation and the effluent is concentrated until a sludge is obtained. The disadvantages of the system consist of the possibility that some volatile substances may be removed with the vapor, and the high cost of the fuel used for evaporation. The advantages include the possibility of recovering all water-dissolved substances.

Reverse Osmosis

Reverse-osmosis treatment concerns the use of semipermeable membranes that tend to balance the different dilution existing between two liquids (pure water and polluted water) present in two containers separated by the semipermeable diaphragm.

If higher pressure than the osmotic one is applied in the container in which the polluted liquid is, there is an inverse outflow of water: The polluted water tends to concentrate with a mechanism similar to evaporation, although in evaporation, energy is supplied as heat, whereas in reverse osmosis energy is supplied as pressure.

Plant Configuration

The treatment plant of an agrofood factory usually contains a combination of the above processes that is chosen according to the type of effluent to be treated, based on the following effluent characteristics:

- Flow-rate and volume
- Physical and chemical properties
- Quality required
- Capital plant investment availability
- Running and management costs
- Plant site
- Presence of specialized and available personnel
- Presence of centralized treatment plants.

A purification plant, designed on the basis of the above elements, involves three subsequent stages:

- Primary treatment, used to prepare the substances suspended in effluents, is performed by mechanical processes.
- Secondary treatment, intended to convert the biodegradable organic substances into stable products, usually is performed by biological plants, after chemical–physical treatment.
- Tertiary treatment is aimed at improving the effluent, so as to make it suitable for discharge. The third stage usually is implemented by chemical or physical processes (chlorination, activated carbons, ultraviolet rays).

The products coming out of the treatment plant include a treated effluent that, according to the specific process concerned, is suitable for discharge into streams or into municipal treatment plants; a stable sludge, which may be contained in ditches or tanks, is accumulated near the plants and should be reused or disposed of.

5.1.3 Composting with Reference to Plant Solutions

Composting, which originates from the need to have manure substitutes for organic soil fertilization, may be carried out by facilities of different technological levels that should, in any case, give rise to an organically stable product in accordance with the law.

Facilities generally are constructed following technological solutions consistent with the characteristics of the product to be treated, the degree of automation required, and plant costs in terms of operation and management [10].

However, for a rational conversion of the organic substance to stable humus, it is first necessary to check that the biomass used for mixing do not contain toxic or harmful

products. The carbon:nitrogen ratio in the mass being oxidized should be close to 25, and moisture should be kept at around 65% [11].

It is to be pointed out that the conversion should be monitored carefully; during thermophilic oxidation the control of temperature is very important: In the first oxidation hours, it should reach 60°C, to decrease slowly during the subsequent stabilization period.

Temperature, therefore, should be adequately controlled by means of systems for thermal-energy removal or supply; such a control should be integrated with an oxygen supply adequate to prevent the onset of anaerobic conditions and with a periodic control of moisture content to prevent a slowing down or even a break in the microbial activity [12].

The optimal values for mass aeration in static reactors range between 0.1 and 0.22 dm³/m³s. If the air inflow is greater than 0.22 dm³/m³s the mass cooling is too high and oxidation processes are not carried out adequately, whereas if inflows are below 0.02 dm³/m³s, the humic acids formed are poor and the product is not sanitized [13].

The exposure of the mass being oxidized to the air causes a moisture loss of 50% of the initial content in 14 days, 11 days, and 9 days respectively for air inflows of 0.02, 0.1, and 0.22 dm³/m³s.

This moisture loss is necessary, because the mixture starts fermentation with 65% water content, whereas the final compost should have a water content below 30%. Nevertheless it should take place progressively and along with the evolution of the organic-matter transformation processes [13].

In open composting plants, the mixture of the materials to be oxidized is placed on impermeabilized concrete aprons and drained into trapezoidal piles 3 to 5 m in width and not exceeding 2.5 m in height.

In this system, the occupied area piles volume ratio is 0.5, considering that the piles may reach a length of 60 to 100 m, is 0.5 and a density of 1030 kg/m³. An adequate control of the piles temperature is difficult using this system. The nonhomogeneous ventilation of the product inside the piles, cause the formation of pockets that undergo abnormal fermentation and also may be affected by anaerobic processes [14].

In closed plants, fermentation takes place in a wholly controlled medium, usually in reactors. In horizontal-axis plants the material is distributed in piles not exceeding 3 m.

Horizontal reactors usually consist of an impermeabilized concrete bed adequately equipped with a draining system of percolation liquids. The area in which the material is distributed is indicated on this by trenches [15].

Trenches may be either rectangular or elliptic. In both plant types, the management is usually dynamic in that the product is periodically turned and moved towards the outlet.

In these plants the aeration of the fermenting mass is provided by simple turning; in this case, although a disturbance of the microorganism's activity is possible, there is no problem related to the excessive heat loss, because piles are localized in a protected environment in which the greenhouse effect, produced by the transparent surfaces, causes an increase in environmental temperature and a quicker attainment of the heat levels required to sanitize and activate the mass humification process.

Turning normally is carried out using appropriate turning machines that can greatly reduce labor use and fully automate the system. The machines used for this purpose generally are mounted on wheels sliding on rails or in tracks; the machine advance

rate is very slow; usually it does not exceed 20 mm/s, and in some plants it falls to 6 mm/s.

The system of turning and displacing the product may consist of dovetailed blade-shaped tools forming a 35-degree angle with vertical on a crankshaft. In these machines, the combined action of the advance and rotation (in the opposite direction to the advance direction) of the shaft imposes a trajectory on the blades that causes them to penetrate the oxidizing mass with a subsequent turning action, and displacement of the mixture aggregates towards the back [16–17].

5.1.4 Importance of Agroindustries and Size of the Problem

The present trend is to carry out processing in areas other than farms. Such a trend induced a concentration of processing industries in highly productive units that subsequently cause a concentration in the production of effluents high in organic matter.

In Table 5.1 the production values in the most industrialized countries are reported. They show that treatment problems mainly concern the Mediterranean and European countries in general.

A basic analysis of the type of processing shows that although for winery, fresh-fruit, and vegetable processing industries, waste results from the washing of plants and products, olive-oil mill effluents mainly consist of the water contained in the fruit. This means that olive-oil production has a higher organic load than those of the other agroprocessing industries.

Hence for wineries the plants usually proposed are similar to urban wastewater plants, whereas for the olive-oil industry the processing technology requires a more careful analysis, the organic load being very high and not easily biologically degradable.

Table 5.1. Productions of olive oil and wines (in thousands of metric tons)

	Wine			Olive Oil			
	1979–81	1992	1993	1994	1979–81	1992	1994
World	34,844	29,185	26,235	25,737	1825	1989	1947
North and Central America	1910	1875	2080	2031	2	3	4
Canada	45	38	39	39	—	—	—
United States	1678	1654	1850	1800	—	1	3
South America	3325	2203	2307	3045	19	11	11
Asia	222	479	536	509	193	228	286
Japan	55	50	45	47	—	—	—
Europe	24,626	21,591	18,316	17,295	1435	1526	1416
France	7060	6493	5331	5545	2	4	2
Germany	700	1348	1000	1130	—	—	—
Italy	8075	6869	6262	6000	635	469	480
United Kingdom	—	124	116	130	—	—	—
Africa	1143	1139	1046	1051	19	27	14
Oceania	419	500	490	615	—	—	—

From *FAO Yearbook of Production*, vol. 48, 1994.

The solutions usually selected thus are interfaced with partial treatment, complemented by composting techniques of organic substrates or by spreading these on the soil.

5.1.5 Regulations on Effluent Disposal, with Special Reference to Industrialized Countries

The control of agrofood-industry effluent disposal is included within the general framework of national legislation concerning protection of surface or underground water from pollution.

In general terms a license for discharge into a recipient stream in the United States is issued following an assessment based on quality standards aimed at identifying the pollution level in specified parts of the recipient stream (Washington Administration Code ch.: 173-216, 173-220, 173-221, 173-221A, 173-224).

In the European Union the EEC directive 271/1991 has imposed a joint constraint between the regulations in force in the Union countries. Nevertheless, the reception levels of this directive are different among the Union countries due to different preexisting regulations and considering the great diversity in the social and environmental conditions existing in different countries [18].

In general it may be stated that in future the control of industrial discharge, including that coming from agrofood industries, will be increasingly stringent, with a gradual spreading of the principle that “who pollutes must pay.” However, in the case of the national regulations in France, the system refers specifically to pollution standards within management that has its focal point in the tax system, including incentives for effluent purification. On the other hand, authorization for individual discharge in Italy is based on the assessment of the individual-discharge quality, without considering the global evaluation of the environmental impact caused by the accumulation of different discharges in the same stream.

As far as land irrigation is concerned, which is an important way to reuse water in agriculture, particularly in hot and dry countries, there is great difficulty, even among researchers from the same country, in defining the quality of the water. Subsequently, the national laws that regulate this practice are widely different from the quality standards and from the criteria on the basis of which the authorization to dispose is issued.

5.2 Effluents from Wine Processing

P. Catalano

5.2.1 Technological Cycle of Wine Processing and Characteristics of Effluents

The flow chart of the technological cycle of winemaking is shown in Fig. 5.1. Some operations of this cycle shared, in principle, by different products were unified to simplify the scheme and to emphasize the effluent flows at the different stages better [19, 20, 21]. The following processing stages in particular are pointed out:

- Discharge
- Preparation of the must (crushing with or without grape stalk, possible separation of the must from the solids for off-skins fermentation, fermentation of the must

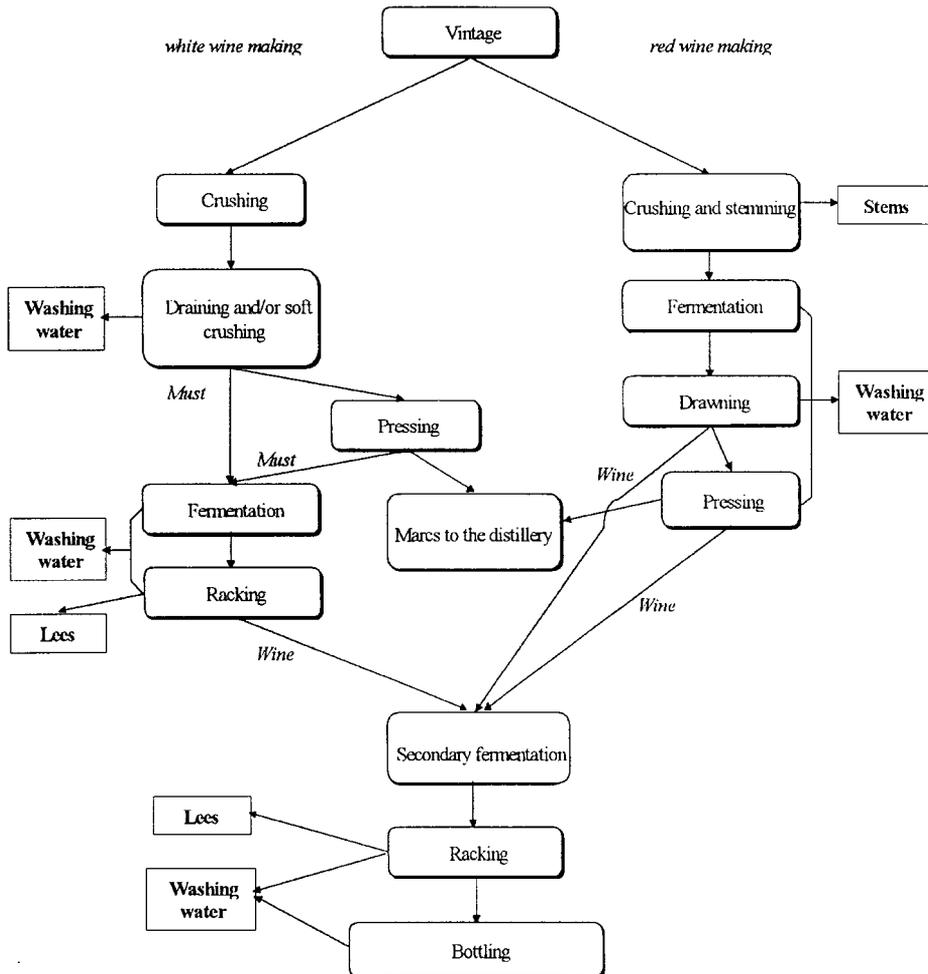


Figure 5.1. Vine making and effluents produced: block diagram.

in the tumultuous stage, settling and separation of the yeast biomass: lees from fermentation, and pomace, in the case of the fermentation with maceration, to be exhausted by straining and/or pressing);

- Stabilization (spontaneous or caused by refrigeration and with fining treatments; settling of tartrates and colloidal substances);
- Conditioning (filtration treatment, bottling: washing of containers, corking, labeling and capsuling, possible thermal treatment of wine at the filling stage, use of SO_2 as antiseptic).

The first two processing stages generally are shared by all wineries, although conditions among wineries vary. The former also depends on the different technological solutions adopted. However, both water and pollution loads are greater in small plants than in larger ones.

Table 5.2. Average characteristics of winery effluents

Origin of the Effluent	pH	Suspended Matter (kg/m ³)	Chemical Oxygen Demand (COD) (kg/m ³)	Biological Oxygen Demand in five days BOD ₅ (kg/m ³)	Polyphenols (Gallic Acid) (g/m ³)	BOD ₅ /COD
Wine making: vat-washing water (0.250 m ³ per tank of 25 m ³)	3.8	12.80	11.50	7.50	59	0.7
Condensing water of must pans	4.0	0	22.08	12.36	160	0.6
First racking: vat-washing water	3.7	17.50	15.17	9.73	119	0.6
Second racking: vat-washing water	3.7	3.46	16.33	9.32	185	0.6
Other wastewaters: vat-washing water after the 3rd racking (0.150 m ³ per tank of 10.8 m ³)	4.4	0.52	4.91	2.51	70	0.5
Vat-washing water after sale (0.150 m ³ per tank of 10.8 m ³)	5.8	0.16	2.47	0.95	24	0.4
Vat-washing water of the rosé wine after bentonite clarification	4.5	0.44	23.96	12.80	88	0.5
Washing water of the diatomite filter	3.7	28.4	19.48	10.09	111	0.5
Washing water of the bottling plant	9.1	0.58	12.20	7.05	0	0.6

Because the water is mainly vat- and container-washing water, the surface area to be washed per unit volume of the container becomes smaller if the size of the containers is increased.

The characteristics of the effluents from these two stages to be considered in designing the treatment plant are reported in Table 5.2 and mainly refer to the washing operation in the routine processing cycle [22, 23].

The effluents mainly consist of washing waters for squares, floors, platforms, and preliminary processing equipment, such as hoppers, storage tanks, crushers, stemmers, presses, fermentation tanks, and must processing and separation machines, wine from fermented pomace, and clarification of musts and racking [24, 25].

Wine bottling and must concentration, on the other hand, are present in wineries with a complete processing cycle, and they differ considerably in terms of effluent type, because the first stage discharges effluents with a high amount of biodegradable detergents and soda with a highly basic pH and residues of labels, glue, and so forth, whereas the second conditioning stage yields high amounts of water containing sulphur dioxide with concentrations varying from 10 g/m³ to 100 g/m³ [26].

Therefore, in these two stages, specific pH-neutralization actions and a chemical-oxidation plant to reduce the SO₂ are required.

Table 5.3. Variability of pollution load versus type of wine making

Type of Effluent	pH	Settling Solids (g/m ³)	BOD ₅ (kg/m ³)	COD (kg/m ³)
Wine making with maceration (1st racking)	3.8	60	8.5	15.0
Wine making off-skins (1st racking)	4.2	20	1.6	3.1

Pollution peaks also are found in the waters coming from the washing of filters and tanks after bentonite clarification, because in the first two stages, in particular, there is an average content of 25,000 to 28,000 g/m³ of suspended organic matter rich in tartrates, tannin, glycosides, polyphenols, pectin, and so forth having a BOD₅ content of no less than 10,000 g/m³ [26].

It is also to be observed (Table 5.3) that in wine making with maceration, heavier pollution loads are produced [27].

Moreover, both the amount of effluent discharged and the pollution load are highly variable in the course of the year within the same winery because of the seasonal production characteristics, especially for small wineries (Figs. 5.2 and 5.3).

5.2.2 Polluting Factors and Reduction of the Pollution Volume and Effluent Load

The major pollution factors, regarding the different processing stages, can be classified as follows.

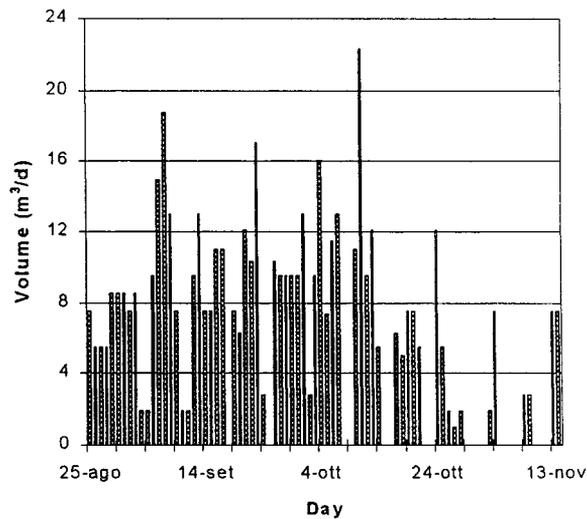


Figure 5.2. Variation in the volume of wastewater after primary settling in the period from September to November. (Adapted from [28])

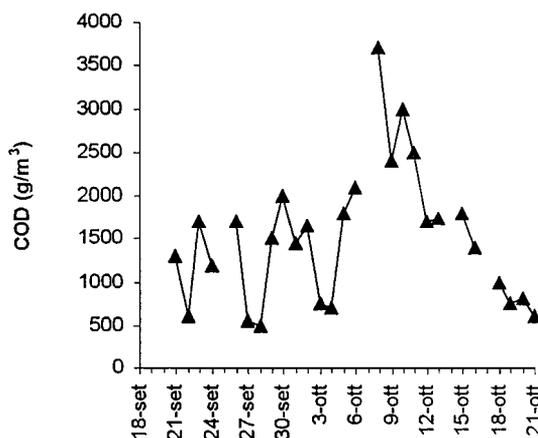


Figure 5.3. Variation in the pollution load in the period from September to December. (Adapted from [29])

Coarse Solid Residues

These residues mainly consist of pomace, grape seeds, and stalks that can be separated by means of mechanical treatment, such as screening or primary settling. The removal of these residues is, however, necessary mainly because of the large size of residues, which could cause significant damage to pipes and effluent-conveyance channels, as well as to the pumping stations [30].

Sludge and Lees

These represent about 40% of the total pollution load. Spreading on the soil and thickening by filtration are the types of treatment often associated with these stages. In the second case, in particular, filter presses or rotating filters [30] are used.

Potassium Bitartrate

The removal of potassium bitartrate encrustation through washing of vats is a significant source of pollution [31]. In this case, it is essential to adopt all possible precautions to reduce the volume of discharged waters beforehand, permitting potassium bitartrate recovery at the same time.

Washing Techniques

Use of nozzles with adequate water-jet characteristics is necessary, so that the mechanical action exerted on the surface to be cleaned is adequately distributed (size and distribution of drops of water, velocity and width of the opening angle of the jet, etc.). If possible, high-temperature vapor also could be used, thus saving a large amount of water; however, if the thermal action is increased considerably, the mechanical action is reduced strongly.

Lining

The adhesion force of encrustation (and thus the related detachment energy) is closely connected to the roughness of the surface to be cleaned. For instance, the epoxy-resin lining of vats makes cleaning operations easier; the same is true for the electrolytically

smoothed stainless steel. Water savings can be reasonably large, in some cases even as high as 50%.

Water Run-off

The reduction in the volume of effluents to be discharged also is possible through water run-off. The technique of temperature control through cold-water run-off at the surface of the fermentation vats still is quite widespread due to the considerably low investment costs [31]. However, in order to reduce wasting water that, although having a low pollution load, still should be purified, the run-off water should be recycled. Recycling prevents higher investment costs in the transformation of the cooling system from the classical run-off system into direct or indirect expansion techniques using refrigerating fluid and an appropriately designed refrigerating plant. However, it is worth mentioning the drawbacks of such an expansion technique, in addition to those of higher running costs: the need to clean the outer surfaces of the vats, the impossibility of attaining the thermal powers required with vats with great volume:surface ratio; the need for continuous control; and difficult automation.

Cleaning of the Support Surfaces

Other surfaces to be cleaned that are huge sources of pollution because of the high amounts of water and detergents used are the bearing floors of support structures and passageways. In this case, it is essential to optimize the concentration of detergents according to their contact time with the surface to be cleaned, to choose temperatures that improve the solubility of the removed substances in the washing waters, and to use high-temperature techniques (vapor) or high-mechanical action techniques (water nozzles).

Recycling of Potassium Bitartrate Washing Waters

Washing waters resulting from the extraction of potassium bitartrate usually are not conveyed to the purification plant because they still contain the previously mentioned salt; they are reused for further crystallization operations, because of the high added value of this substance.

Use of Ecological Filters

A considerable reduction in the volume of effluent discharged, as well as of its pollution load, is possible through the use of ecological filters, in the technological cycle of wine for must filtration, for example submerged filters with expulsion of the coat by centrifugal action. In this way, the amount of water used for washing filters is minimized.

5.2.3 Treatments for Winery Effluents Purification

The different solutions adopted for purification of winery effluents are summarized in Fig. 5.4 [26, 27].

Pretreatment Operations

As previously mentioned, effluents resulting from the processing treatment contain suspended solids of different sizes, such as pomace, grape seeds, and stalks, that have to be removed before the final purification treatment [32, 33].

Therefore, screening is the initial operation to be applied to winery effluents. The amount of material that can be retained depends on the size of the screens; in particular,

Table 5.4. Major size and operational characteristics of screens for the collection of coarse materials

	Hand-Operated Screens	Mechanically Operated Screens
Bar thickness (mm)	5–15	5–15
Bar depth (mm)	25–75	25–75
Bar opening (mm)	20–60	10–30
Inclination (degrees)	45–60	70–90
Water velocity upstream (m/s)	0.3–0.5	0.5–1
Head loss (m)	0.1–0.2	0.1–0.2

Source: [29].

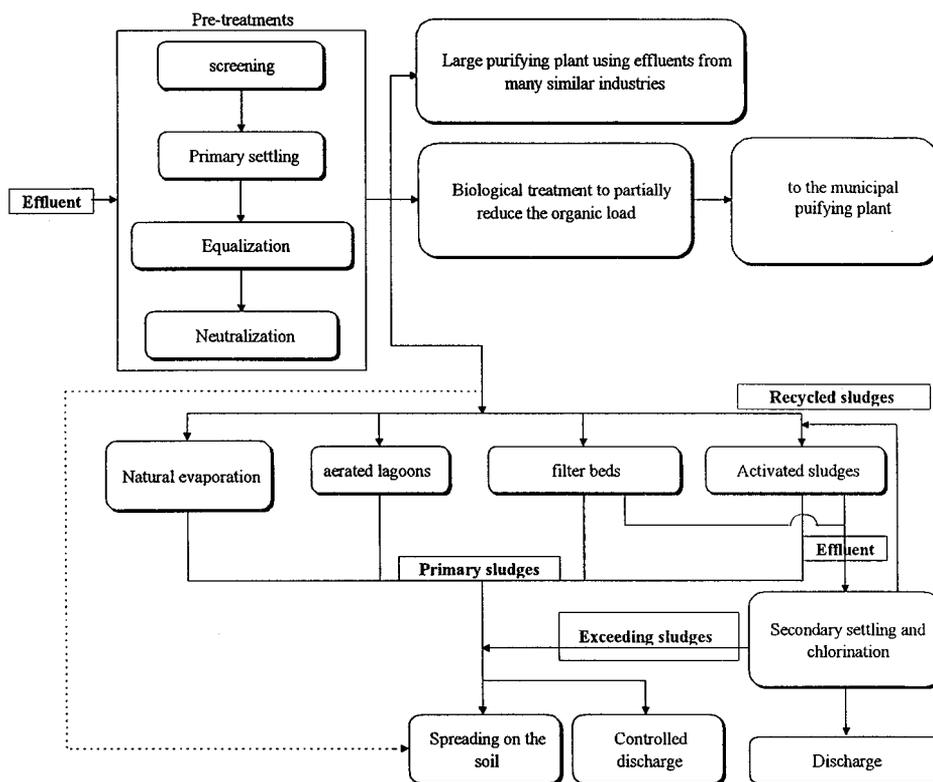


Figure 5.4. Flow charts of the different plant alternatives proposed to treat winery wastewater.

larger-span screens, the bar types, allow hand or mechanical screening of coarse material (Table 5.4), whereas the screens with smaller meshes, the mesh or the perforated-plate types, are required for removing fine solids and are mechanically operated [33].

Fine screens, to which the same general remarks apply as for the mechanically operated ones, except for the size of meshes, which are generally smaller than 10 mm, are generally of the drum type. Removal is performed by means of scrapers or by centrifugal action.

A primary settling tank then is installed to reduce the pollution load by eliminating most of the suspended solids that are not retained by screening. For subsequent treatment (autonomous or performed by other plants, either private or public) the pollution load is reduced by limiting both the design and the installation and running costs.

However, primary settling produces sludge that requires a subsequent stabilization treatment, which is too expensive to be applied to small plants for which the connection with the sewage network is more profitable.

The settling tanks [33, 34] consist of circular concrete or iron tanks, with the bottom slightly inclined towards the conveyance zone of the sludge settled by means of scrapers; these are not installed in small-sized plants and have quite deep tanks to allow the collection of sludge in the middle.

The residence time in the settling tanks generally varies according to the type of biological treatment envisaged for the effluent: 1.5 to 2 hours for the primary sedimentation made upstream of the activated sludge oxidation plant, 3 to 4 hours upstream of the filter beds.

In the case of plants close to the maximum size, the influence of wind on the velocity of the liquid in the tank also has to be considered; it might, therefore, be necessary to install a windbreak across the main wind direction.

The effluent of the settling tanks is accumulated in appropriate homogenization tanks [33, 35], in order to reduce both the discharge fluctuations and pollution load as much as possible. They are constructed in such a way as to avoid undesirable recycling through air insufflation (air flow variable from 1 to 2 m³/h per cubic meter of the tank depending on the level of the liquid) or with floating-type surface turbines (supplied power variable from 20 to 40 W/m³ of tank capacity), in order to prevent anaerobic processes.

The volume of the equalization tanks has to be evaluated according to the volume of discharged effluent and the desired reduction in discharge and pollution-load fluctuations of the effluent.

The effluent is subsequently neutralized by adding adequate doses of sulphuric acid or lime depending on the pH of the effluent. This process, which is required if additional biological treatment is envisaged, generally is carried out automatically by the real-time measurement of the pH by pH meters that control the opening and closing of electric valves for the regulation and dosage of reagents [26].

Separate processing is carried out on the effluents resulting from the concentration of musts that have to be subjected to the chemical oxidation process of SO₂ before moving to the subsequent treatment. The plant generally consists of a waterproof reactor equipped with a mechanical stirrer to allow the best contact of the reagents with the effluent. The oxidizing reagent most commonly used is sodium hypochlorite, which is injected into the reactor, according to the measured pH, by means of adequate control instruments [26].

Finally, a technique that allows the volume of effluent moved to the secondary treatments to be considerably reduced consists of natural evaporation through evaporation panels [36]. These are characterized by a large amount of evaporating surface compared with their sizes and allow about 50% of the effluent to be concentrated at low installation and management costs, especially if automated, with the same reduction in the final treatment costs [37].

This technique, however, has the typical disadvantage of lagooning, that is, the emission of malodorous volatile substances, and thus the impossibility of having urban settlements in proximity to the plant, to be evaluated according to the different national laws. Also the low effluent discharges for each evaporation module (10 units are not normally exceeded)—2 to 5 m³/d per module—could be a disadvantage of the evaporation plant.

Secondary Treatment Operations

These treatments are recommended for large plants (autonomous treatment) or for purification platforms to which the effluents from a number of plants are conveyed, not necessarily from wineries, that are of an equally significant size.

Generally, in the case of wineries, aerobic biological systems are used (filter beds, lagooning, activated sludge) in which the organic matter is metabolized through aerobic microorganisms in the presence of oxygen and the possible addition of nutrients.

Secondary treatment can be made by means of an anaerobic process; however, these methods require a constant effluent discharge and high operating temperatures as well as rather long residence times, leading to costs that are unacceptable for winery-effluent purification.

For these reasons, the anaerobic purification methods are not recommended for winery effluents.

Filter Beds

Filter beds [26, 33, 38] consist of basins or containers generally cylindrical in shape with a large amount of contact-surface filtering material per unit volume of filter bed, a high degree of roughness to help the adhesion of the biological film, its long duration, and relatively low cost, on which the effluent is made to percolate through adequate distributors arranged on revolving arms (Fig. 5.5).

The effluent-distribution system has to assure a uniform spraying of the bed with such specific discharges (referred to as the volume of the filter bed) to guarantee complete wetting of the filling material.

In the case of traditional filling, intermittent distribution has to be applied: in this case, small feeding tanks equipped with siphons are installed. Their volume is equal to the amount that can be supplied each time in order to guarantee complete wetting and filling times equal to the average retention time of the effluent in the filter bed.

The arms, on which the nozzles are mounted, rotate at variable speed according to the filter material and the bed depth, from 1 to 30 revolutions per hour.

Therefore, gravel is used (resulting from the breaking of nonflaking rocks, volcanic material, blast-furnace slags, etc.) as a filling material for the traditional type filter bed.

The size of the filter bed should not be too great, to allow a high surface:volume ratio, nor too fine, to prevent clogging: the size of material generally used is between 0.05 and 0.20 m (surface:volume ratio variable from 80 to 90 m²/m³, void fraction 50%, bulk density about 2500 kg/m³). It is also important for the material not to be too porous, to prevent shattering during sudden temperature changes.

The height of traditional filter beds depends on the possibility of having optimal ventilation: for average sizes of 0.05 m, a height of 2 m is adopted, whereas for average sizes of 0.08 m the height can be even 3 m or more if the filter is equipped with an

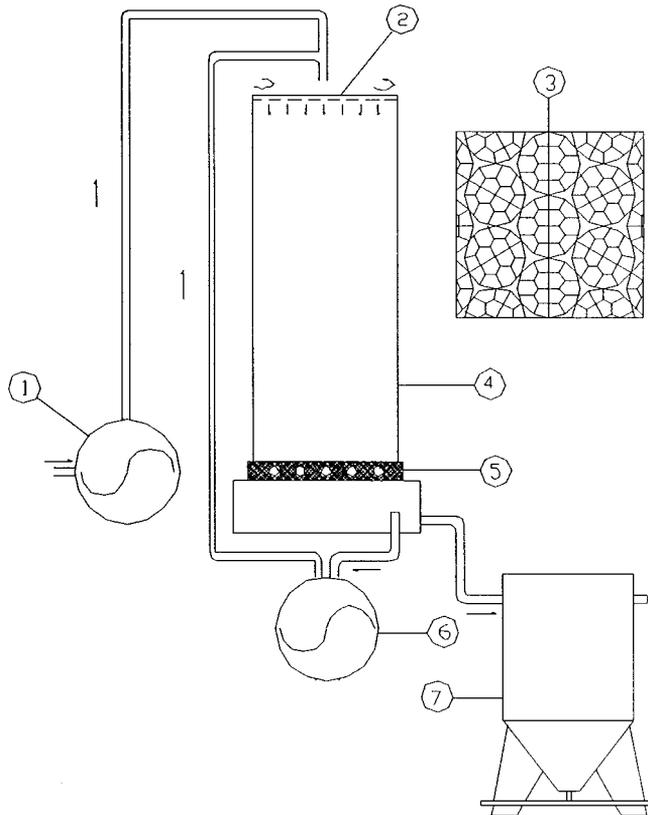


Figure 5.5. Filter-bed plant: feeding pump (1), spreading system (2), section of the filter bed (3), cylinder containing the filter bed (4), air circulation system (5), effluent recycling pump (6), settling tank (7).

adequate forced-ventilation system. Traditional filters are used if the polluting load of the effluent is not high, to avoid an excessive growth of the biomass that would cause bed clogging.

For higher organic loads, preformed plastic components generally are used as filling material (Table 5.5), with vertical pipes having an inner honeycomb section, vertical slabs consisting of crossed undulated slabs to form parallelepiped blocks.

Table 5.5. Major characteristics of plastic filling materials

Type of Filling	Type of Material	Specific Surface (m^2/m^3)	Void (%)
With vertical pipes	PVC	220	94
With vertical slabs	PVC	90–135	98
With vertical slabs	Polystyrene	89–189	94

Table 5.6. Operating characteristics of filters

	Low-load Filters	High-load Filters
Hydraulic load ($\text{m}^3/\text{m}^2\text{d}$)	1–4	8–40
BOD ₅ ($\text{kg}/\text{m}^3\text{d}$)	0.08–0.4	0.4–4.8
Effluent recycling ratio (%)	0–50	100–400
Required electrical power (W/m^3)	2–4	6–20
Purification efficiency (% of removed BOD ₅)	90–95	60–70
Film detachment	Intermittent	Continuous
Type of supply	Intervals not greater than 5 min	Continuous
Nitrification	Complete	Moderate
Characteristics of the sludge obtained	Black, highly oxidized	Dark, not completely oxidized, tendency to septicity

Filter beds are classified into two categories, low-load filters ($\text{BOD}_5 < 500 \text{ g}/\text{m}^3$) and high-load filters. Operating characteristics are reported in Table 5.6.

A modified version of filter beds is the biodisk [38], in which the biological film support surfaces consist of a set of disks ($\Phi = 2\text{--}3 \text{ m}$) half-dipped in the effluent contained in a horizontal semicylindrical tank. By rotating ($n = 2\text{--}5 \text{ rpm}$) around the axis of the shaft on which they are dovetailed, they oxygenate the liquid film during the stage of contact with water that adheres to them during dipping.

Activated Sludge

Oxidation of organic load with the help of activated sludge [33, 39] occurs in a tank in which oxygen is supplied by insufflation of air and dispersed in the liquid mass by submerged turbines or porous porcelain or plastic diffusers or through mechanical aerators (Fig. 5.6).

In the tank, the biological mass (activated sludge) is regenerated continuously by recycling a part of the sludge separated in the subsequent secondary settling.

The concentration of the organic load generally is kept around $2.5 \text{ kg}/\text{m}^3$ and never exceeds $4.5 \text{ kg}/\text{m}^3$ in any case.

The efficiency in removing the pollution load is between 85% and 92%, with a retention time of between 4 and 6 hours. To achieve reductions in the region of 99%, much longer aeration times are required (for total oxidation processes) of about 24 hours [33, 40].

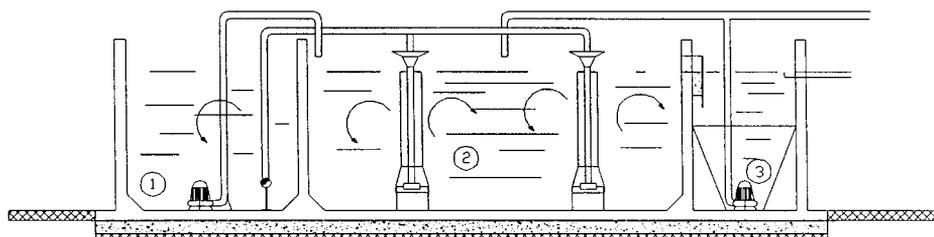


Figure 5.6. Activated sludge plant: homogenization tank (1), oxidation tank (2), settling tank (3).

The shape of the oxidation tanks depends on the aeration system used. In the case of diffused-air aeration, long and narrow tanks are used in which the width:height ratio is 1 to 2 for diffusers installed along one of the longest sides, whereas higher values may be possible in the case of diffusers uniformly spread on the bottom of the tank.

In the case of mechanical aeration, the tanks are circular in small plants or rectangular (almost square) in other plants, where the width (or diameter):height ratio varies from 1.5 to 5 with increasing turbine size. Moreover, especially in small plants, or sometimes in large units with subsequent oxidizing treatment, combined (or single-basin) plants are used in which the aeration tank and the secondary settling tank are merged [26].

The level of the liquid is maintained almost constant within an interval of about 0.10 m by regulating weirs through which the aerated mixture passes via the conveyance pipes to the secondary settling tank. This type of regulation becomes essential if fixed mechanical aerators are used.

The main parameters characterizing the activated sludge-purification process are (Table 5.7):

- *Retention time*, τ_r (h), in the aerated tank:

$$\tau_r = \frac{24 \cdot V}{\dot{V}} \quad (5.1)$$

where V (m^3) is the volume of the tank and \dot{V} the effluent delivery (m^3/d)

- *Biomass concentration*, MLSS (mixed liquor suspended solids, g/m^3) and MLVSS (mixed liquor volatile suspended solids, g/m^3) in the aerated tank
- *Organic load*, U , referring to the unit mass of biomass ($\text{g BOD}_5/\text{g MLSS}$):

$$U = \frac{24 \cdot \text{BOD}_5^i}{\tau_r \cdot \text{MLSS}} \quad (5.2)$$

where BOD_5^i is the organic load of the effluent reaching the aerated tank

- *Organic load*, C_v , referring to the unit volume of the aerated tank ($\text{g BOD}_5/\text{m}^3$):

$$C_v = \frac{\text{BOD}_5^i}{V} \quad (5.3)$$

- *Recycled sludge ratio*, R (%):

$$R = 100 \frac{\dot{V}_r}{\dot{V}} \quad (5.4)$$

where \dot{V}_r (m^3/d) is the recycled sludge delivery

- *BOD₅ removal efficiency*, η (%):

$$\eta = 100 \frac{\text{BOD}_5^i - \text{BOD}_5^o}{\text{BOD}_5^i} \quad (5.5)$$

where BOD_5^o is the organic load of the effluent leaving the secondary settling tank.

Table 5.7. Typical values of some operating parameters of the activated sludge process

Process	Aeration System	U (g BOD ₅ /g MLSS · d)	C_v (kg BOD ₅ /m ³)	SS_f (g/m ³)	τ_r (h)	Amount of Air to give (m ³ /kg BOD ₅ removed)	R (%)	η (%)
Typical (Example I)	Air diffusion or mechanical aeration	0.2–0.4	0.3–0.6	1500–3000	4–8	50–60 ^a	25–50	85–95
Typical (Example II)	Air diffusion or mechanical aeration	0.2–0.6	0.8–1.9	3000–6000	3–5	35 ^a	25–100	85–95
High-load	Mechanical aeration	0.4–1.5	1.5–1.5	4000–9500	0.5–2		100–500	75–90
Long-term aeration	Air diffusion or mechanical aeration	0.05–0.15	0.15–0.4	3000–6000	18–36	75–110 ^a	75–150	75–90
Pure oxygen	Mechanical aeration	0.25–1.0	1.6–4.0	6000–8000	1–3		25–50	85–95

^a Only for air diffusion

Table 5.8. Operational characteristics of aerated lagoons

Depth of the basin (m)	1.8–6
Range of allowable temperature (°C)	0–40
Range of allowable pH	6.5–8.0
Hydraulic residence time ^a (d)	3–10
Concentration of suspended solids in the effluent ^b (g/m ³)	80–250
Purification efficiency of BOD ₅ (%)	80–95

^a Coincides with the age of sludges because recycling is zero.

^b Including algae, microorganisms, and suspended solids, residues of the influent.

Aerated Lagooning

Unlike the activated-sludge oxidation process, in aerated lagoons the concentration of microorganisms is not controlled by the recycling of sludge; they are exclusively produced by the degradation of the biological substrate entering with the fluid [26, 33].

Generally, aerated basins are made of earth and impermeabilized. They supply the oxygen required to maintain the aerobic conditions through floating turbines or diffused aeration.

Therefore, in the aerated lagooning, energy consumption can be attributed mainly to the mixing energy of the mass, because of the low total-solid content resulting from the lack of sludge recycling. On the contrary, in activated sludge plants main energy consumption comes from the oxygen transfer required for the biological process.

Aerated lagooning, thus, has the advantages of having a low level of sludge production and not being affected by the variation in load and discharge. However, the main disadvantages include the large area of land occupied and sanitary problems (malodorous lagoons). In Table 5.8 the operational characteristics of aerated lagoons are given.

Land Distribution

In addition to the previously mentioned possibilities, soil spreading also should be mentioned [30, 41]. There are two solutions currently adopted for direct spreading of effluents on the ground: transportation and spreading by means of tank wagons and land distribution. In both cases the conditions that have to be respected in order to avoid soil system damage are the absence, in the land subjected to spreading, of water-logging sites or infiltration to the groundwater; uniform distribution of the effluent on the whole surface affected by spreading; and an amount not exceeding 1000 to 1500 m³/ha.

When spreading by the tank wagon, it is particularly necessary to equip the winery with an aerated basin of a sufficient capacity to contain the effluent produced in about 30 days at full capacity. It is also necessary to determine the capacity of the tank depending on the total area available, on the overall amount of effluent to be distributed, and on the time required for the operation.

If spreading on land, the irrigation network has to be adequately designed according to the previously mentioned parameters, as well as to the type of emitter used, the possibility of real automation depending on the effective daily (or hourly) load, and also

Table 5.9. Characteristics of the influent to the treatment plant

	Minimum	Maximum
COD (g/m ³)	2000	9000
BOD ₅ (g/m ³)	1200	6000
Total suspended solids (g/m ³)	200	1200
Nitrogen (g/m ³)	25	70
Total phosphorus (g/m ³)	5	10
pH	7	12.9
Discharge (m ³ /d)	4	30

Adapted from [26].

meteorological conditions. There is a higher investment cost but lower running costs than with spreading by tank wagon.

5.2.4 Design Example of Treatment Plant for Winery Effluents

Let us take the example of a winery that processes 3000 m³ of wine (2400 m³ white wine, 350 m³ red wine, and 250 m³ sparkling wine) [40].

Pomace and fermentation lees are channeled to distillation, whereas potassium bitartrate is precipitated and recovered to be sent to tartaric acid-producing plants. Washing of vats, premises, and equipment is carried out using phosphate-free products, and the effluents coming from the buildings attached to the winery are not mixed in.

Table 5.9 reports the typical parameters of the effluents to be treated.

The following is provided:

- Coarse screen with automatic cleaning
- Equalization tank (70 m³) in order to make the pollution load and the discharge constant over a period of 24 hours, thus allowing the purification plant to operate even in the periods of nonprocessing; equipped with diffused-air aerators
- Three oxygenation tanks with complete mixing (70 m³), one with double store (combined: 33 + 37 m³); these are of the modular type, thus allowing the exclusion of one or more tanks according to the effluent discharge, variable because of the seasonal nature of winery activities; equipped with membrane diffusers situated on the bottom of the tank for the diffusion of extremely fine air bubbles
- A circular upward-flow settling tank (25 m³), with a cone-shaped bottom equipped with an outlet for excess sludge

Given the high flexibility of the plant, the tank supply system has to be controlled automatically in order to allow the rapid adaptation of the plant to new operating conditions. Purification efficiency of the COD is estimated to be about 98%.

5.3 Effluents from Olive-Oil Processing

G. C. Di Renzo

5.3.1 Extraction Systems and Effluent Composition

Oil extraction from olives does not require great quantities of water. The effluent produced during the extraction presents a high organic load, however, which has to be

Table 5.10. Sources of effluent from olive-oil processing

Sources	Value ^a (%)
Washing water	0–10
Olive water	40–90
Water added during extraction	
Traditional process	0–10
Continuous process	0–60

^a Expressed as percentage of weight of milled olives.

treated in order to avoid damaging the quality of the water into which the effluent is discharged. In Table 5.10 a source distribution of olive-oil processing effluents (OPEs) is shown. The tap water required for the olive-oil extraction varies mainly in relation to the type of extraction system (continuous or discontinuous) [42].

Use of the continuous system (centrifugal extraction) generally requires an increase in the amount of tap water added to the olive paste before the extraction. This is necessary to reduce the viscosity of olive paste and to facilitate the separation of the oil-water mixture from the solid part (pomace). Generally the OPEs produced are 900 to 1200 kg/ton of processed olives. By using different volumes of processing water the OPE concentration of organic compounds is changed by 3% to 12%.

In the discontinuous process (using a hydraulic press) the volume of the effluent is reduced to 500 to 700 kg/ton of processed olives; however, the organic load concentration dramatically increases.

OPEs generally are discharged into a tank in which they are maintained for a period of 2 to 6 days. In this phase the fat floats because oil–water emulsion is partially broken and suspended solids settle, so organic load is reduced by about 15%. All the sugar is subject to uncontrolled fermentation, and a large amount of alcoholic compounds are produced (e.g., ethilic and methilic alcohols). Tables 5.11 and 5.12 show the average composition and characteristics of OPEs [43–46].

Table 5.11. Average composition of effluent from olive-oil processing (in kilograms per ton)

	Italy	Spain
Water	880–970	830–900
Organic substances	20–100	70–150
Sugar	8–61	20–80
Nitrogenous substance	4–13	12–24
Acids	3–8	5–15
Pectins	5–8	10–15
Fats	0.2–10	0.3–10
Inorganic Substances	10–20	10–20
Potassium salts	6–14	5–10
Phosphate	1–3	1–3
Others	2–3	2–3

Sources: [43–46].

Table 5.12. Effluent characteristics from olive-oil processing

Parameter	Value
pH	5.0–5.5
Specific weight	1.020–1.049
Dry extract (kg/m ³)	61.1–129.7
COD (kg/m ³)	60–180
BOD ₅ (kg/m ³)	20–55
Reducing sugar (kg/m ³)	15.9–35.8
Total phenolic compounds (g/m ³)	2.7–6.2
O-diphenols (g/m ³)	2.0–4.8
Alcohol precipitate (g/m ³)	24.6–30.4
Ashes (kg/m ³)	6.4–20.1
Organic nitrogen (g/m ³)	404–544
Total phosphorus (g/m ³)	185–485
Sodium (g/m ³)	36–110
Potassium (g/m ³)	950–2470
Calcium (g/m ³)	69–162
Magnesium (g/m ³)	90–194
Iron (g/m ³)	14.0–32.9
Copper (g/m ³)	1.59–3.12
Zinc (g/m ³)	2.06–3.57
Manganese (g/m ³)	1.55–5.32
Nichel (g/m ³)	0.57–0.78
Cobalt (g/m ³)	0.18–0.43
Lead (g/m ³)	0.42–1.05

In order to quantify the magnitude of the problem related to OPE organic load, it must be considered that 1 ton of milled olives produces about 36 kg BOD₅, which corresponds to a daily load of about 650 inhabitants. So a small olive-oil extraction plant that mills 10 ton/d of olives produces the same polluting load as a town of 6500 inhabitants [42].

5.3.2 Water Saving and Recycling in Processing

In the past 20 years efforts have been directed at lowering extraction costs by replacing the discontinuous system with a continuous one. The olive paste generally is separated into three fractions (three-phase extraction), oil, OPEs, and pomace, by using centrifugal technology. In order to preserve the advantages of centrifugal extraction, either reducing the amount of water added until it is completely eliminated, a three-phase centrifugation with recycling of OPEs, or two-phase extraction (Fig. 5.7) is suggested.

The three-phase centrifugation with recycling of OPEs soon after centrifugal extractor outlet permits a reduction in OPE production by about 40% to 60%, with a consequent reduction of tap-water use in the process. The pollutant load in the water is similar to that produced in the discontinuous system [47].

The two-phase extraction requires the centrifugal extractor to be modified from those used for the three-phase extraction (for control of differential rotational speed between bowl and screw). However, it allows the tap-water addition to be eliminated or reduced

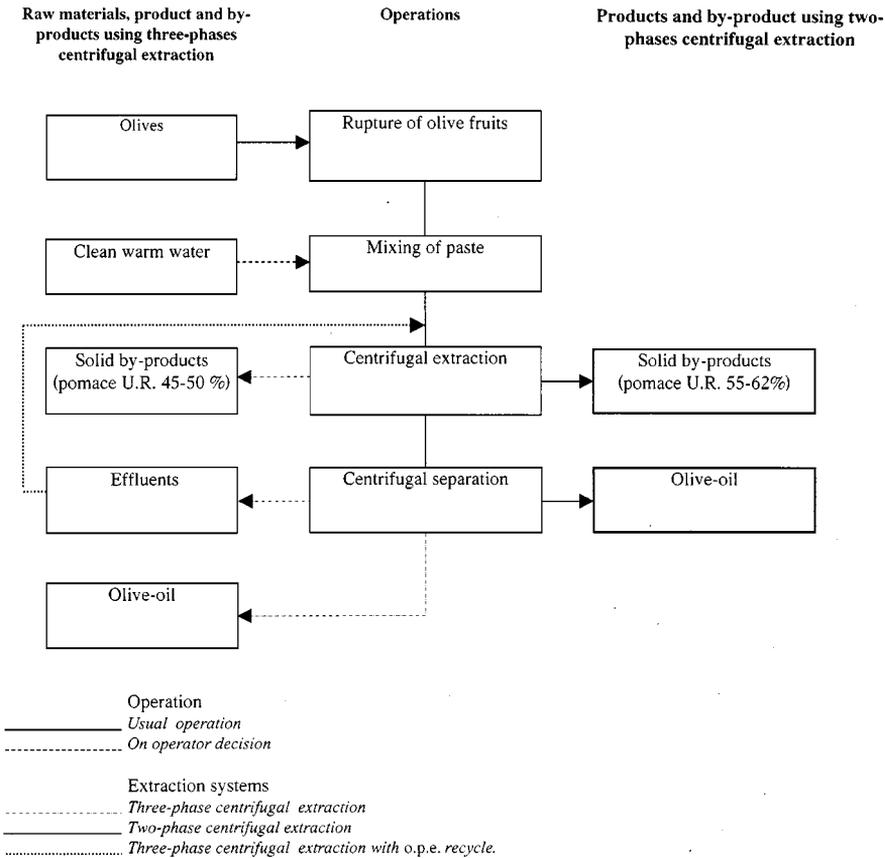


Figure 5.7. Olive-oil centrifugal extraction layout of traditional three-phase, three-phase with recycling of wastewater, and two-phase plants.

to minimal levels in the case of olives with low moisture content. There is the added advantage that it eliminates OPE discharge, although it leaves a moisture content of about 60% in the pomace [48]. The higher moisture content makes the chemical extraction of the residual oil in the pomace more expensive.

5.3.3 Reuse for Land Irrigation

At present the use of OPEs for land irrigation still is being studied, not only as a disposal system for these effluents but also as a way to improve the physical and chemical characteristics of the soil. Before use it is a good practice to subject the OPE to adequate treatment of grinding, flotation, and sedimentation, in order to facilitate the separation of oil and coarser materials [49, 50].

OPEs contain an appreciable quantity of mineral elements, which could replace some of the nutrients generally provided by fertilization. OPEs are actually very rich in potassium, and they also contain nitrogen, phosphorous, and magnesium, but the

most important component is organic matter that could improve soil structure and soil microbial population development [51].

The positive effect could be reduced by the following characteristics:

- Salinity, which could reach a high concentration in the soil and produce flocculation of the clayey soil fraction [52, 53]
- High acidity, i.e., a low pH of about 4.9 for OPEs produced from traditional plants; a pH of about 5.6 for OPEs produced from centrifugal extraction
- Abundance of polyphenols, which present a notable phytotoxic effect on crops [44]

The literature on OPE utilization for land irrigation is quite recent. It presents different conclusions about the appropriateness of performing this operation. Negative considerations are based on the presence of a high organic load in the OPEs and on the presence of polyphenols, which have a notable phytotoxic effect on seed germination and crop growth [52–54].

Table 5.13 shows the different results obtained by several authors regarding volume and condition for distributing OPEs on fallow land [55, 56], land planted with olive trees [44, 45, 57, 58], or land before planting and in presence of vegetable crops [59, 60]. In some cases the positive results have been obtained by neutralizing the acidity of OPEs with lime before application on different crops [44].

Table 5.13. Volumes and periods of olive-oil processing effluents connected to field irrigation advised for different crops

	Volume	Period	Notes	Ref.
Olive	<100 m ³ /ha			41
	>400 m ³ /ha			51
	<800 m ³ /ha			
	100–200 dm ³ /tree		Neutralizing the acidity	40
	>100 m ³ /ha			54
Vine (var. <i>verdeca</i> , var. <i>montepulciano</i>)	<150 m ³ /ha		Increase production and sugar content	54
	<150 m ³ /ha			
Salad	<200 m ³ /ha	Distributed until 10 d before transplanting		41
Rye-grass (<i>Lolium italicum</i>)	>200 m ³ /ha	Distributed until 45 d before seeding	Trials executed in pot and greenhouse	41
	<800 m ³ /ha			
Wheat	>20 m ³ /ha	During the bunching phase		55
	<320 m ³ /ha			
Wheat	>20 m ³ /ha	Distributed until 30 d before seeding		56
	<100 m ³ /ha			
Corn	>20 m ³ /ha	40–50 d before seeding		55
	<320 m ³ /ha			
Corn	>20 m ³ /ha	Distributed until 20 d before seeding		56
	<100 m ³ /ha			
Barley	>20 m ³ /ha	During the bunching phase		55
	<320 m ³ /ha			
Sunflower	>20 m ³ /ha	40–50 d before seeding		55
	<320 m ³ /ha			

Fiestas [44] points out the need to perform the distribution considering the crop phenological phase, especially in terms of germination for the vegetable crops and the vegetative activity renewal for arboreal ones, which must be changed from around 2 to 3 weeks.

Bonari [59] concludes from field trials that distributing up to 320 m³/ha of OPEs during the heading phase on wheat or barley, and on uncultivated soil before corn and sunflower seeding, does not produce negative effects on the crops' biological cycles or on their productions. However, he points out the necessity of extending the experimentation to different season courses and for a large number of years.

Catalano et al. [58, 61] verify that the organic components of the OPEs are decomposed in a short time and that in soil subjected to distribution there is shown to be an increase in the nitrogen, phosphorous, and potassium contents. The utilization of OPEs causes a phytotoxic effect on the potato and almost all weeds. It also results in a vine- and olive-production increase in terms of quantity and quality.

5.3.4 OPE-Treatment Systems

Regarding the high organic load of OPEs, generally the treatment system is not a single operation but a sequence of interrelated operations. Collection, screening, equalization of effluent flow, and sedimentation are treatment steps preceding biological or physical treatment. The following solutions have been proposed after considering this difficulty [42]:

- Large plants, designed to process a large amount of urban and agroindustry effluents. These plants treat effluents produced by different industries; they allow optimization of the treatment, recovery of the by-products, and the use of a more rational management process. The running costs are reduced, but these plants require additional transport cost for effluents.
- Small plants, designed to process the effluents produced by a single olive-oil processing industry. These plants have a lower cost than the large ones. The treatment system is simplified, and generally by-products are not recovered. Often the energy costs are higher than those of the large plant, but they can be reduced by using renewable fuels.

Biological Treatment Systems

In the biological treatment systems, the organic matter is transferred to the biomasses by interfacial contact and associated adsorption. The efficiency and the speed of this biological process depend on the extension (related to a concentration gradient of the substances to be removed from one phase to the other) and the quality (related to the oxidation of organic matter and synthesis of new cells) of the interface between water and biomass [62].

Organic substances concentrated at the surface are absorbed by the biomass. Absorbed substances are decomposed during the metabolic activity of microorganisms and are used for cell growth and multiplication. End products of decomposition are released into the water, and the gases escape if the partial pressure in the contiguous atmosphere is lower than that inside the water [62].

The low biodegradability of OPEs makes the use of traditional biological systems alone more difficult. Those systems are not adequate to stabilize the organic load in a short detention period [63, 64]. For this reason they generally are diluted with urban effluents or preceded by treatment for reducing the poliphenol content.

Activated-Sludge System

In the activated-sludge system, the purification process is controlled by regulating sludge waste and return. Generally the sludge is recirculated for a few days. In this system the floc suspension and activity depend on the flocs' dimensions. Too-large or too-heavy flocs tend to become inactive and anaerobic [62].

Temperature and availability of oxygen and essential minerals are the most important parameters influencing biomass activity and floc growth [65].

The minimum mineral requirement is a ratio of BOD₅:N:P equal to 100:5:1. In OPEs the ratio of BOD₅:N:P is 100:1:0.5; large amounts of minerals are required in order to create the best growing conditions for the active biomass [65].

The presence of substances that inhibit biomass growth requires preliminary treatment of OPEs for the degradation of phenolic compounds, tyrosol, and hydroxytyrosol that occur in the highest proportion and are the main antibacterial compounds present in the OPEs.

Martinez-Nieto *et al.* [66] report that by using *Aspergillus terreus* in aerobic conditions 69% of total phenol content can be degraded. COD and BOD₅ degradation are 53% and 67% respectively.

Due to the high pollutant load in OPEs and the low BOD₅:COD ratio (0.30–0.35), aerobic treatment on untreated OPEs requires an elevated energy cost for oxygenation. Moreover, the long treatment time required by OPEs makes it necessary to construct expensive large volume tanks.

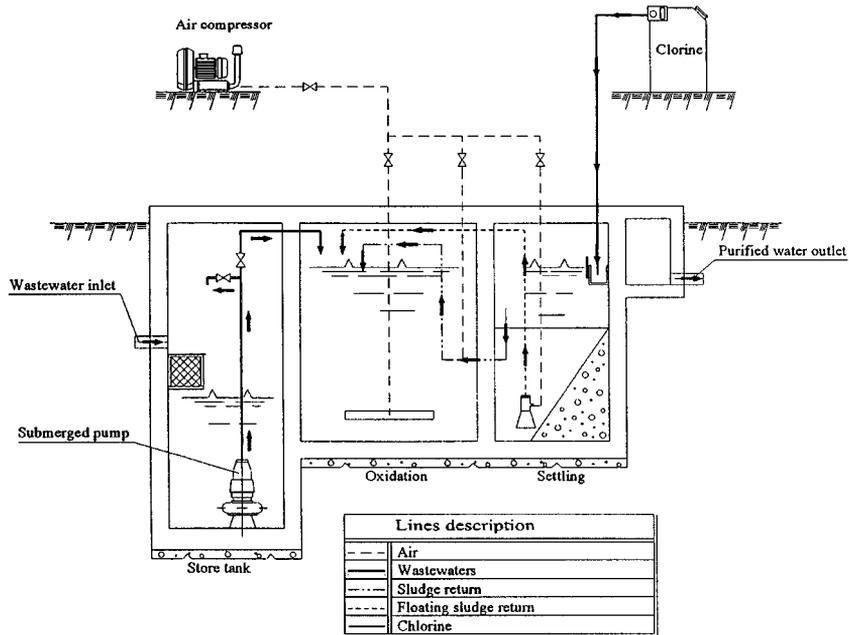
Treatment of the activated-sludge type on OPEs has been carried out as follows:

- As the final purification treatment on effluents produced in other purification systems (anaerobic treatment and concentration treatment) (Fig. 5.8)
- In a mixture with urban wastewater [63–65]; good results are reported in refs. [67] and [68] with the OPE:urban wastewater ratio of 0.033 as volume and 2.7 as BOD₅. The efficiency of BOD₅ removal is 75% with a projected BOD₅:suspended solid ratio of 0.5 (Fig. 5.9).

Anaerobic Digestion System

Anaerobic purification of effluents normally is carried out at a slower rate than aerobic purification [70]. During the anaerobic purification, gases are released and foul-smelling intermediate substances are produced [62]. Subsequent treatment of the effluent by aerobic biological processes is required.

Before carrying out anaerobic digestion, dilution or pretreatment is required because of the organic load of OPEs. Pretreatment generally is based on microorganism inoculation that operates in aerobic conditions. Borja *et al.* [71] find that inoculation with *Geotrichum candidum* provides a partially purified effluent that is subject to a faster anaerobic process than the original OPE [71].



(Courtesy of Depureco s.r.l.)

Figure 5.8. Compact plant for aerobic treatment with activated sludge of pretreated waters.

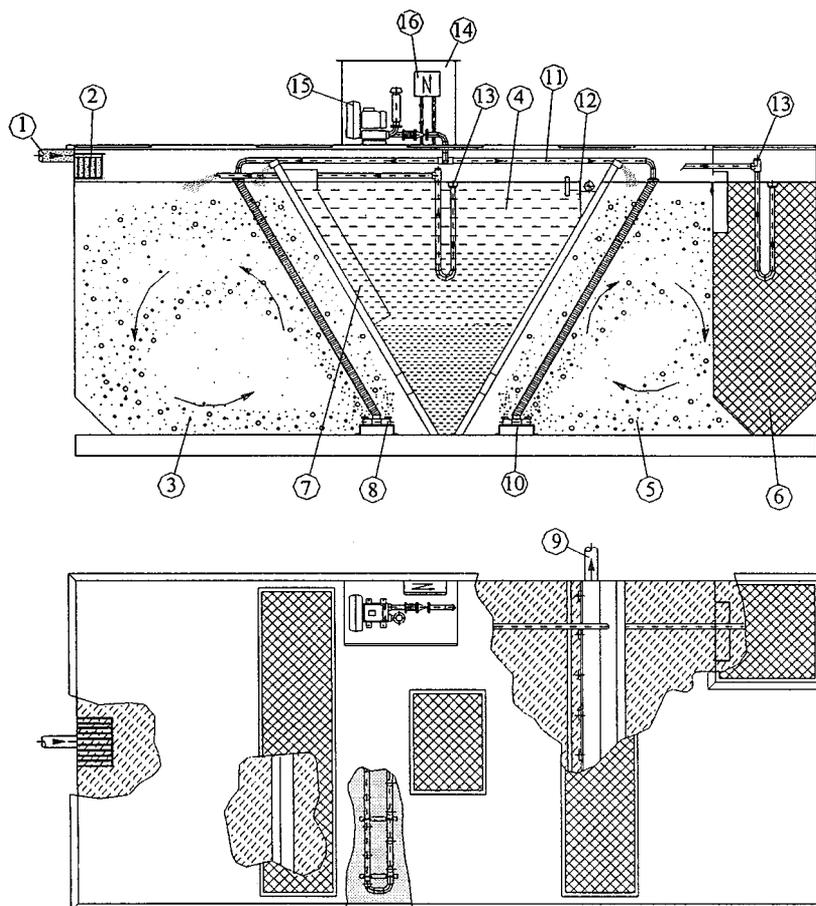
Padilla *et al.* [72] use a treatment with sepiolite or bentonite for reducing the biomass inhibitor substances (phenolic compounds). They report that the use of sepiolite totally eliminates tyrosol in 12 days and hydroxytyrosol in 24 days.

Hamdi *et al.* [73] find that *Aspergillus niger* grows on undiluted OPE, yielding reductions in COD and phenolic compounds of 61% and 58%, respectively. Use of this system as a pretreatment for anaerobic digestion is suggested to create a better environment for growing methanogenic bacteria. Methane production is increased by 50% compared with the control during anaerobic digestion of OPEs prefermented by *Aspergillus niger* [74] by adding a microbial consortium (obtained by enrichment culture on syringate of termite gut material) to the control inoculum originating from OPE sludge in a ratio of 1:4.

Purification of OPEs using anaerobic systems is possible because the polluting load consists of soluble and colloidal substances. These characteristics suggest the use of high-load reactors such as the upflow anaerobic sludge blanket [75].

The anaerobic plant generally consists of an activated and digestion unit (gastight tank), a degasifier, a sludge-separation tank, and a return sludge pump (Figs. 5.10 and 5.11). The process must be kept at a temperature of 35 to 37°C, so heat should be supplied, and combustible gases may provide the necessary heat.

The anaerobic process is continuous, the plant is continuously fed with OPEs. Inside the tank the OPEs are mixed with the biomass in order to improve the contact between biomass and organic-waste substances. Good results for purification of OPEs are reported with the average concentration of 34 kg BOD/m³ [76].



(Courtesy of Sereco s.r.l.)

Figure 5.9. Compact plant for aerobic treatment with activated-sludge of OPEs mixed with urban wastewater. Cross-section (*upper*) and plan view (*lower*). 1, Wastewater inlet; 2, screen; 3, oxidation; 4, settling; 5, sludge digestion; 6, sludge settling; 7, overflow deflector; 8, air diffuser; 9, outlet-treated water; 10, air-distribution pipe to the diffuser; 11, air main pipe; 12, skimming blade; 13, skimmer; 14, equipment room; 15, air compressor; 16, electric control panel.

Anerobic treatment effluent has a pH of 7.2 to 7.5, a COD of 4000 to 5000 g/m³, a dark red color; and an absence of suspended solids. Anaerobic digestion of OPEs requires little energy or mineral nutrients. Modest quantities of sludge are produced during the process (Fig. 5.12) [77].

Before storing, the biogas produced is dehumidified [72]. The quantity produced is generally about 10 m³/m³ of OPEs treated, with heating power equivalent to 6 kg of combustible oil [76].

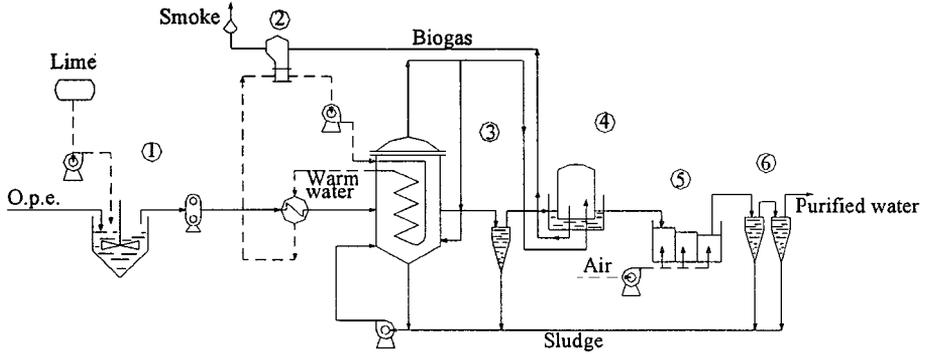
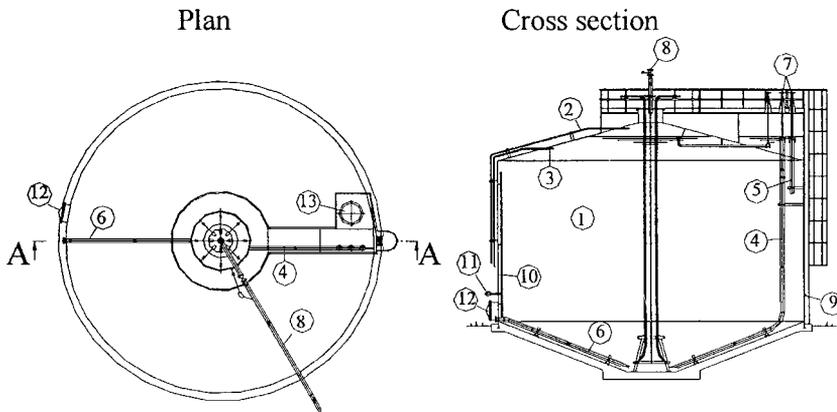


Figure 5.10. Anaerobic plant layout. 1, Screen and store tank with lime addition for pH neutralization; 2, boiler for warm-water production; 3, anaerobic digester; 4, biogas tank; 5, plant for aerobic treatment with activated sludge; 6, sludge settling.



(Courtesy of Sereco s.r.l.)

Figure 5.11. Anaerobic digester. 1, Digester; 2, OPE inlet; 3, recirculated sludge inlet; 4, bottom sludge outlet; 5, middle sludge outlet; 6, pipe to feed sludge to heat exchanger; 7, telescoping valves; 8, biogas outlet; 9, temperature-measuring device; 10, insulation; 11, sample access; 12, bottom manhole; 13, top manhole.

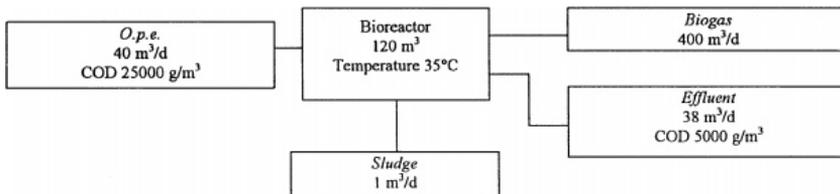


Figure 5.12. Mass balance in anaerobic treatment. (Adapted from [70])

The seasonal nature of OPE production (generally no longer than 100 days) is compatible with anaerobic digestion because of the reduced decay of microorganisms responsible for the process during the period of inactivity [76].

The use of a reactor with microorganisms immobilized on clay supports (sepiolite) improves the methane-production rate [71, 78].

In order to operate the plant year-round and to avoid the start-up period (required after several months of plant inactivity), anaerobic codigestion may be carried out by operating on swine effluents mixed with OPEs or dairy effluents depending on their availability. An organic loading rate of 3.84 kg COD/m³d was found to be safe for a digester operating on a year-round basis [79].

Borja and Gonzalez [80], comparing an anaerobic filter reactor (AFR) and an anaerobic contact reactor (ACR) for OPE purification find that a steady state is reached more quickly using the ACR process than with the AFR process. The daily methane production and COD removal measured with the AFR were greater than those measured with the ACR. The application of ACR and AFR results in yields, respectively, of 0.18 and 0.34 m³ methane/kg COD. The AFR yields a biogas with a higher percentage of methane and effluents with lower volatile fatty-acid and solid contents than the ACR. Additional advantages of the AFR over the ACR include the elimination of mechanical mixing and sludge settling and return.

Georgacakis and Dalis [81] describe a mesophilic anaerobic digestion of supernatant and sludge obtained from OPEs after 10 days of settling in fixed bed- and plug flow-type anaerobic digesters. The biogas produced is about 2.28 m³/m³ of digester volume, the chemical oxygen demand reduction is 94%, and a final effluent COD is 4 kg/m³ [81].

Concentration by Evaporation Systems

Concentration by evaporation systems consists of separation of the OPEs into two fractions, water and sludge. The major fraction of organic-waste substances remain in the sludge. Generally the evaporated water still requires biological treatment in order to decompose organic compounds evaporated with water. The sludge is treated in composting plants or used in a burner with combustible oil for heat production [82]. Concentration can be carried out in batch evaporators or continuous evaporators.

The batch evaporators are short vertical tube evaporators that contain a heating element. They normally have a large central downtake and vertical tubes from 0.9 to 1.5 m in length. The effluent's movement through the heat exchanger is controlled by an internal or external circulating pump. The pressure inside the evaporator can be reduced to 0.7 bar in order to improve the distillation process.

The sludge remains in the batch evaporator until the concentrate reaches the established concentration; then it is discharged into a second tank for storing. The vapor separated from OPEs is aspirated by a vacuum pump, condensed, cooled, and then transferred to the biological treatment system (Fig. 5.13).

Continuous evaporators are generally multistage flash evaporators. These are usually long vertical tube machines. Effluents are heated in a surface heat exchanger and flashed

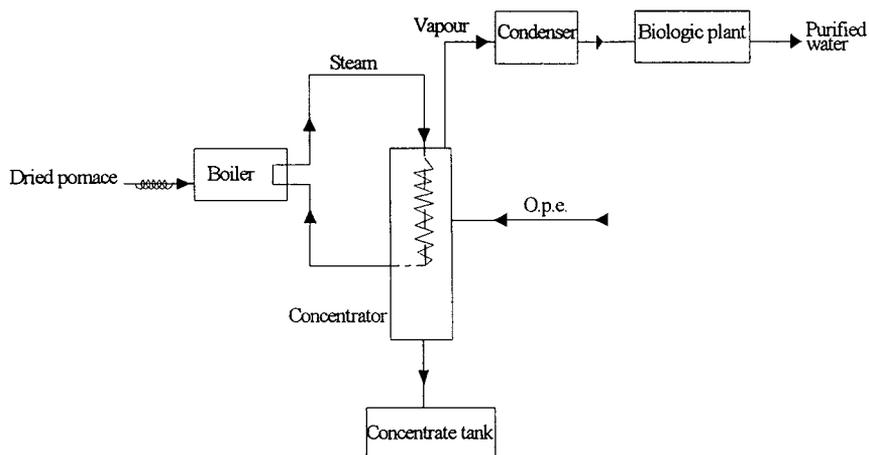


Figure 5.13. Plant layout of a batch evaporator for OPE concentration using renewable fuel (pomace).

from one effect to the next from the last stage to the first. They permit an energy savings for effluent concentration [83].

The steam consumption regarding the mass of evaporated water varies, according to the number of effects used (Table 5.14).

The OPE plants generally consist of two or three effect-flash evaporators. Each evaporation unit consists of a flash-evaporator column, a shell-end-tube exchanger, a pump for sludge circulation, and a pressure valve that controls the degree of sludge concentration (Fig. 5.14).

Flash-evaporation columns and shell-end-tube exchangers are used because the concentration has to be maintained in rapid relative movements compared with the heat-exchange surfaces in order to avoid fouling.

The following end products (Table 5.15) are obtained through the concentration in a triple-effect concentrator:

- Water–alcohol mixture, which is obtained in the first effect and contains a varying amount of alcohol ranging from 2.5% to 15%; the alcohol presence is due to the

Table 5.14. Steam consumption in relation to the number of effects in concentration of olive-oil processing effluents

Number of Effects	Steam Consumption (kg steam/kg evaporate water)
1	1.20
2	0.65
3	0.36

Table 5.15. Average characteristics of elements in evaporation process

	Olive-Oil Processing Effluents	Concentrate	Water-Alcohol Mixture	Evaporated Water
Density (kg/m ³)	1060	1190	985	1000
Dry matter (kg/t)	80	530	—	—
Calorific value (kJ/kg)	—	19.28	—	—
Alcohol content (kg/100 kg)	—	2.5–4.0	—	—
COD (kg/m ³)	100	—	60	2

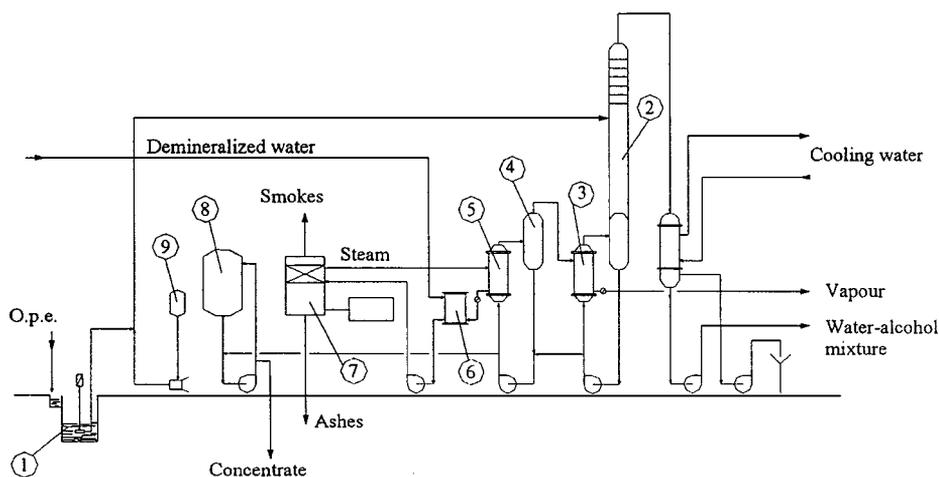


Figure 5.14. Plant layout of two-effect flash evaporator. 1, Screen and store tank; 2, first effect with distillation column; 3, first effect shell-end-tube exchanger; 4, second effect; 5, second effect shell-end-tube exchanger; 6, feed heater; 7, boiler for steam production; 8, concentrate tank; 9, antiffoaming agent tank.

alcoholic uncontrolled fermentation of sugars in the effluent soon after the discharge in the storing tanks

- Evaporated water, which is separated in the second and third effect, with a COD of 1.5 to 2.0 kg/m³
- concentrate with a moisture content of 0.5 to 0.6 kg/kg.

Table 5.16 shows the average mass and energy balance on the basis of an 800 kg/h feeding rate.

Concentration by Ultrafiltration and Reverse Osmosis

Vigo *et al.* [84, 85] propose an ultrafiltration system for small olive-oil producing units. They obtained low energy consumption, oil recovery, and permeate with low organic load by using a polyvinylidene fluoride membrane. The flux of permeate is high, but it requires biological treatment to reduce the organic load still present.

Table 5.16. Mass and energy data of the concentration process of olive-oil processing effluents

	Mass		Energy	
	Flow Rate (kg/h)	Percentage	MJ	Percentage
Input				
Combustible oil	30	—	1218	67
Concentrate recycled	63	—	525	29
Electrical energy	—	—	86	4
Output				
Water–alcohol mixture	280	35	41	—
Evaporated water	400	50	67	—
Concentrate (53% of dry matter)	100	15	352	—
Thermal energy losses	—	—	65	—

Note: With plant-feeding rate of 800 kg/h.

Massignan *et al.* [86] successfully treated OPEs with reverse osmosis, using pre-treatment with calcium chloride ($0.01 \text{ mm}^3/\text{m}^3 \text{ CaCl}_2$) at room temperature. They report that natural stabilization for 4 months also induces an effective separation of gel substances and an increase in efficiency of reverse osmosis. Using flat membranes for reverse osmosis mod. DDS (De Danske Sukkerfabrikker) 20-0,36 LAB, they obtained a permeate flux equal to $0.385 \text{ m}^3/\text{m}^2\text{d}$, with a COD rejection of 98%.

Amirante and Di Renzo [87] describe a reverse-osmosis plant with a capacity of $4 \text{ m}^3/\text{h}$ developed for industrial application. It consists of the following treatment: flocculation of suspended solids, prefiltration using a rotary-vacuum precoated filter, reverse-osmosis filtration or microfiltration, and activated-sludge biological treatment of permeate (see Fig. 5.15). Flocculation of suspended solid is carried out with $10 \text{ g}/\text{m}^3$ of a cationic organic polymer with a detention time of 1 minute.

Due to the high concentration of solid particles in OPEs, prefiltration is carried out with a rotary precoat filter of 10 m^2 area. About 130 kg of perlite is used as a filter-aid

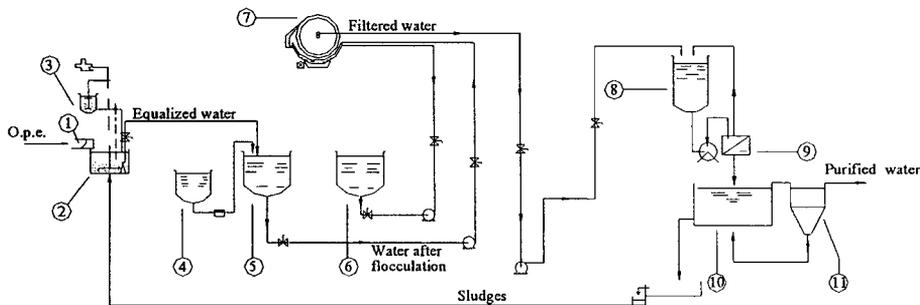


Figure 5.15. Plant with reverse osmosis developed for industrial application. 1, Screen; 2, store tank; 3, lime tank; 4, flocculant tank; 5, flocculation tank; 6, precoat tank; 7, rotary precoat filter; 8, filtered water tank; 9, reverse-osmosis unit feed tank; 10, reverse-osmosis unit with membranes; 11, aerobic treatment unit; 12, sludge-settling tank.

Table 5.17. Average operating data of filtration treatment of olive-oil processing effluents with 3% of dry matter

Characteristic	Value
Drum rotation speed (rpm)	1.6
Blade advancing speed ($\mu\text{m/s}$)	4.5
Prefiltered permeate flow rate (m^3/h)	3
Specific flow rate ($\text{m}^3/\text{h}\cdot\text{m}^2$)	0.3
Drum vacuum pressure (MPa)	0.06
Dry-matter filtered effluent (%)	2

precoat. It is spread on the surface and produces a 60 mm–thick coat applied to the filter drum. This cake, mixed with the solid particles deposited on the surface, is dressed by the knife blade microadvancing to expose the cylindrical surface of the clean filter aid. Filtration is finished when the blade has removed all of the panel. The time required ranges from 3 to 6 hours, with dry matter in the OPEs ranging between 2% to 10%. The data on filtration is reported in Table 5.17 using OPEs with 3% dry matter.

Operating with a higher dry-matter content (8%) of OPEs, a specific flow-rate value of $0.15 \text{ m}^3/\text{h}\cdot\text{m}^2$ has been measured. The COD removed in this operation ranged between 30% and 80% depending on the concentration of organic load in treated OPEs.

The reverse-osmosis unit consists of three cellulose acetate spiral-wound modules in a fiberglass shell, mounted in sequence, working at a pressure of 5.8 MPa. The permeate rate measured was $0.060 \text{ m}^3/\text{h}\cdot\text{m}^2$, recycling the concentrate with prefiltered permeate. The membrane-cleaning cycle is required after 8 hours of running.

Permeate presents COD equal to 1 to 2 kg/m^3 and requires additional treatment in an activated-sludge biological plant (Table 5.18).

OPE Drying

In order to dry OPEs, they are sprayed on the pomace and dried in a rotary drier. A direct-fired combustion furnace (fed with dried pomace) directly connected to the drier supplies hot combustion gas to the drier. A cyclone recovers the dust from the exhaust gas. The amount of dried pomace burned in the furnace per ton of olives processed ranges from 80 to 200 kg (about 30%–60% of the pomace produced) depending on the volume of OPEs produced and the final pomace moisture content required [88].

Table 5.18. Characteristics of the reverse osmosis process

	Olive-oil Processing Effluents	Filtrate	Permeate	Permeate after Biological Treatment
pH	5.30	5.2	3.6	7.2
COD (kg/m^3)	100	35	1.2	0.2
BOD (kg/m^3)	36	10	0.05	0.025
Dry solids (%)	6	2	0.05	0.05
Fat (%)	0.04	0	0	0

Table 5.19. Comparison of requirements of olive-oil processing effluent treatment systems

	Land	Energy	Labor	Labor Qualification	Construction Cost	Operating Cost
Land distribution ^a	*****	**	****	*	**	**
Activated sludge ^b	****	**	**	**	*	**
Anaerobic digestion	****	* ^c	**	****	***	**
Concentration by evaporation systems	**	*****	**	*****	*****	*****
Concentration by reverse osmosis	**	*****	**	*****	*****	*****
Drying	*	****	**	**	****	****

Sources: [61, 63, 79, 83–85] and information from others' and author's experience.

Note: ** low; **** medium; ***** high.

^a Evaluation include machines for transport and distribution in field.

^b Olive-oil processing effluents mixed with urban wastewater.

^c Recycling the biogas or the pomace in the process.

5.3.5 Comparison of Treatment Systems

OPEs can be treated by different systems. In industrialized countries the limiting factors are generally national regulations on purified water standards and disposal and operating costs, especially in terms of personnel. In developing countries high plant costs, labor qualification, plant-management difficulties, and availability of spare parts represent important aspects that have to be evaluated when choosing a treatment system. Table 5.19 shows the author's evaluated scores for the various requirements regarding different OPE treatment systems, considering the reference source indicated.

The comparison of the different systems in relation to the OPE composition led to the conclusion that it is difficult to define the best solution and design for OPE treatment and purification. All the systems described can be effectively used to treat OPEs, but a system must be chosen and adapted by analyzing the local situation and management qualification [89, 90]. Only in this way it is possible to design and build an efficient plant.

References

1. Amirante, P. 1980. Impianti di depurazione nelle industrie di trasformazione dei prodotti agricoli [Effluents treatment plants for agro-food industries]. Proceeding of seminary: Effluents Treatment for Agrofood Industries, Bari, pp. 9–35.
2. Amirante, P., and B. Bianchi. 1992. Purification of agrofood industries waste water in relation to organic substance recovering. Proceeding of the International Conference of the VI Setct. of CIGR. on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 1–15.
3. Sequi, P. 1983. Il ruolo della sostanza organica nel terreno agrario e i problemi dell'agricoltura moderna [The importance of the organic substance in the soil]. Proceeding of the International Symposium on Biologica Reclamation and Land Utilization of Urban Waste, Napoli.
4. Susmel, L. 1988. Principi di ecologia [Ecology principles]. CLEUP Ed., Padova, pp. 29–79.

5. Indelicato, S. 1992. Treatment and re-utilization of farm effluents and sludge. Proceeding of the International Conference of the VI Setct. of CIGR on Treatment and Re-utilization of Farm Effluents And sludges, Lecce, pp. 159–174.
6. Garvaska, S. M. 1992. Tha sludge from the purification stations for waste water: Characteristics and utilization related on the environment. Proceeding of the International Conference of the VI Setct. of CIGR on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 523–527.
7. Sendic, M. V. 1995. Strategies in agroindustrial waste treatment. *Water Science Technology*. 32(12):113–120.
8. Price, R. 1985. The use of wastes as a source of energy. Proceeding of the International Conference on Biomass, Venice, pp. 214–221.
9. Amirante, P., and P. Catalano. 1994. Valutazione dei prodotti agricoli in relazione ai consumi di energia ed alle risorse impiegate [Evaluation of agricultural products with respect to energy consumption and used resources]. Proceeding of the International Conference on Energy and Landscape, Campobasso, pp. 3–19.
10. Sequi, P. 1991. Criteri di qualità del compost: la maturazione della sostanza organica: Riciclo di biomasse di rifiuto e di scarto e fertilizzazione organica del suolo [compost quality criteria: Waste biomasses re-use and soil organic fertilization]. Pàtron Ed., Bologna, pp. 13–18.
11. Amirante, P., G. C. Di Renzo, and P. Catalano. 1992. Experimental trials for compost production from by-products of slaughter poultry industry. Proceeding of the International Conference of the VI Setct. of CIGR on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 249–260.
12. Amirante, R. 1992. Composting of by-products of olive oil extraction: Legislative, technological aspects and experimental results. Proceeding of the International Conference of the VI Setct. of CIGR on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 287–321.
13. De Bertoldi, M. 1992. Microbiological features of sludges and by-products composting. Proceeding of the International Conference of the VI Setct. of CIGR on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 119–127.
14. Stentiford, E. J. 1986. Recent developments in composting. Proceeding of the International Symposium on Compost: Production, Quality and Use, Udine, pp. 52–60.
15. Stentiford, E. J. 1992. Composting of sludges: trends and process constraints. Proceeding of the International Conference of the VI Setct. of CIGR on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 395–405.
16. Amirante, P., and G. C. Di Renzo. 1991. Tecnologie ed impianti per il riciclo delle biomasse di rifiuto e di scarto [Technologies and plants for by-products re-use]. Riciclo di biomasse di rifiuto e di scarto e fertilizzazione organica del suolo [waste biomasses re-use and soil organic fertilization]. Pàtron Ed., Bologna(I), pp. 221–230.
17. Pudelski, T. 1986. Horticultural use of compost. Proceeding of the International Symposium on Compost: Production, Quality and Use, Udine, pp. 20–29.
18. Salgot, M. 1996. Existing guidelines and regulations in Spain on wastewater reclamation and reuse. *Water Science Technology* 34(11):261–267.

19. Mourgues, J., and J. Maugenet. 1972. Les eaux résiduares des caves de vinification [Effluents from wineries]. *Industries Alimentaires et Agricoles*, 3:261–273.
20. Cochet, P. 1988. Dépollution des activités de vinification et d'élevage des vins [Winerie effluents purification and improvement of wine]. *Revue des Oenologies* 50:11–14.
21. Rambaud, A., J. Bontoux. 1974. Les effluents de l'industrie vinicole [Effluents from wine making]. *Techniques de l'Eau et de l'Assainissement*, 324(3):17–20.
22. Sanna, M. 1975. L'inquinamento e l'enologia [Pollution and enology]. *Vini d'Italia* 98:425–431.
23. Racault, Y., and A. Lenoir. 1995. Evolution des charges polluantes de deux caves vinicoles du Sud-Ouest de la France sur un cycle annuel [Evolution of pollution load of two wineries in the south of France during one year]. *Revue Française d'Oenologie* 152(Mai/juin):16–18.
24. Picot, B. 1992. Pollution engendrée par les établissements vinicoles: Nature, critères d'évaluation et caractéristiques [Wineries pollution: Nature, evaluation criteria and characteristics]. *Revue Française d'Oenologie* 134(janv):5–10.
25. De Stefano, G., and V. Sciancalepore. 1992. Dry matter treatments of reffluent of wine lees processing. Proc. of the Int. Conf. of the VI Setct. of CIGR. on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 89–95.
26. Amirante, P., and G. Scarascia Mugnozza. 1982. Impianti di depurazione delle acque reflue degli stabilimenti enologici [Purifying plants for winery's effluents]. *Vignevini* (5):27–40.
27. Farolfi, S. 1995. La gestione dei reflui enologici sul territorio: Analisi e strumenti [Winery's effluents management: Analysis and means]. Avenue Media Ed., Bologna.
28. Torrijos, M., R. Moletta. 1997. Winery wastewater depollution by sequencing batch reactor. *Water Science Technology* 35(1):249–257.
29. Chudoba, P., and R. Pujol. 1996. Activated sludge plant facing grape harvest period: A case study. *Water Science Technology* 34(11):25–32.
30. Marchetti, R. 1994. Agricultural utilization of effluents and solid wastes produced from enological plants. *Industria delle Bevande* 23(Dec):11–20.
31. Rochard, J. 1992. Reduction de la charge polluante et du volume des rejets dans les caves vinicoles [Pollution load and amount reduction of the wineries' effluents]. *Revue Française d'Oenologie* 134 (Janv):583–588.
32. Conti, F. 1994. Available technologies for the enological effluent treatment, according to the plant production capacity. *Industria delle Bevande* 23(Dec):583–594.
33. Passino, R. 1980. La conduzione degli impianti di depurazione delle acque di scarico [effluent purifying plants management]. Ed. Sci. A. Cremonese, Roma.
34. Eckenfelder, W. W. 1982. *Principles of Water quality Management*. Boston: CBI Publishing Company.
35. Novotny, V., and A. J. England. 1974. Equalization design techniques for conservative substances in waste water treatment systems. *Water Research* 8:325–331.
36. Bianchi, B., and P. Catalano. 1992. Experimental trials on olive oil waste water purifying by means of evaporative panels. Proceeding of the CIGR VI Tech.

- Section on Treatment and Re-utilization of Farm Effluents and Sludges, Lecce, pp. 49–62.
37. Moletta, R., and J. Raynal. 1992. Procèdes de depollution innovants et recherches actuelles dans le domaine vinicole [New purifying processes and actual research for wineries' effluents]. *Revue Française d'Oenologie* 134 (Janv):37–43.
 38. Martin, G. 1982. Point sur l'épuration et le traitement des effluents, vol.1, Lavoisier Ed., Paris.
 39. Gonard, B. 1992. Les traitements del la pollution par procèdes biologiques [Biological processes for effluents treatment]. *Revue Française d'Oenologie* 134(Janv):29–35.
 40. Fumi, M. D., and G. Parodi. 1992. Messa a punto di un impianto ad aerazione prolungata per il trattamento biologico in cantina [Optimization of long-term activated sludge treatment of winery waste waters]. *Industria delle Bevande* 23:305–310.
 41. Dornier, N. 1992. Traitement des rejets en cave vinicole: Épandage - évaporation - raccordement à la station communale [Wineries' effluents treatment: Spreading on soil, evaporation, discharge to a consortia plant]. *Revue Française d'Oenologie* 134(Janv):21–25.
 42. Amirante, P., and G. C. Di Renzo. 1989. Tecnologia e Impianti disponibili per la depurazione delle acque di vegetazione [Plants and technology for olive oil mill effluents]. Proceedings of International Seminary on Olive Oil Mill Effluents Purification, Lecce, pp. 24–57.
 43. del Valle, L. J. 1980. Contaminación de les aguas por el alpehín y posibles soluciones al problema [Water pollution by waste-waters from olive-oil plants and possible ways for resolution of the problem]. *Grasas y Aceites* 31(4):273–279.
 44. Fiestas, J. A. 1977. Depuración de aguas residuales en las industrias de aceitunas y aceites de oliva [Wastewater treatment from olives and oli oils industries]. *Grasas y Aceites* 28:113–121.
 45. Morisot, A. 1979. Utilisation des margines par épandage. *L'Olivier* 19:8–13.
 46. Shammas, N. K. 1984. Olive oil extraction waste treatment in Lebanon. *Effluent and Water Treatment Journal* 24(10):388–392.
 47. Amirante, P., G. C. Di Renzo, and L. Di Giovacchino. 1993. Prove sperimentali su nuovi impianti di estrazione centrifuga dell'olio di oliva [Evaluation of new plants for olive-oil centrifugal extraction]. Proceeding of Vth A.I.G.R. National Meeting 5:265–272.
 48. Amirante, P., G. C. Di Renzo, L. Di Giovacchino, B. Bianchi, and P. Catalano. 1993. Evoluzione tecnologica degli impianti di estrazione dell'olio d'oliva [Technological development of olive-oil plant]. *Olivae* 48:43–53.
 49. Testini, C. 1980. Problemi connessi all'utilizzazione agricola delle acque reflue [Problems related to reuse of wastewater in agriculture]. *Acqua-Aria* 2:241–245.
 50. Sequi, P. 1980. L'acqua, la fertilita del terreno e l'impiego delle acque reflue [Water, soil fertility and wastewater re-use]. *Acqua-Aria* 2:231–240.
 51. Perrone, S. 1989. Lo smaltimento delle acque di vegetazione delle olive [Purification system for olive oil mill effluents]. *Inquinamento* 6:42–45.

52. Pompei, C., and F. Codovilli. 1974. Risultati preliminari sul trattamento di depurazione delle acque di vegetazione delle olive per osmosi inversa [First results of reverse osmosis treatment of olive-oil mill effluents]. *Scienza E Tecnologia degli Alimenti* 4:363–364.
53. Ielmini, M., M. Sanna, and N. Pelosi. 1976. Indagine sulle acque di rifiuto degli stabilimenti di produzione olearia in provincia di Roma: Possibilità di depurazione [Olive-oil processing effluents evaluation in Rome province: Purification opportunity]. *Industrie Alimentari*, 11:123–131.
54. Potenz, D., E. Righetti, A. Bellettieri, F. Girardi, P. Antonacci, L. Calianno, and G. Pergolesi. 1985. Evoluzione della fitotossicità in un terreno trattato con acque reflue di frantoi oleari [Development of phytotoxicity in soil treated with olive-oil mill wastewater]. *Inquinamento* 5:48–35.
55. Marsilio, V., L. Di Giovacchino, M. Solinas, N. Lombardo, and C. Briccoli Bati. 1990. First observations on the disposal of olive oil mills vegetation waters on cultivated soil. *Acta Horticulturae Olive Growing* 286:492.
56. Flouri, F., I. Chatjipavlidis, and C. Balis. 1989. Effect of olive oil mills liquid wastes on soil fertility. Proceedings of International Seminar on Olive Oil Mill Effluents Purification, Lecce, pp. 233–250.
57. Proietti, P., A. Catechini, and A. Tombesi. 1988. Influenza delle acque reflue di frantoi oleari su olivi in vaso e in campo. *Informatore Agrario* 45:87–91.
58. Catalano, M., T. Gomes, M. De Felice, and T. De Leonardis. 1985. Smaltimento delle acque di vegetazione dei frantoi oleari: Quali alternative alla depurazione? [Field distribution of olive-oil mill wastewater: What are the alternatives to purification?] *Inquinamento* 2:87–90.
59. Bonari, E., and L. Ceccarini. 1991. Spargimento delle acque di vegetazione dei frantoi sul terreno agrario [Field distribution of olive-oil mill wastewater]. *L'Informatore Agrario* 13:49–57.
60. Di Giovacchino, L., and L. Seghetti. 1990. Lo smaltimento delle acque di vegetazione delle olive su terreno agrario destinato alla coltivazione di grano e mais [vegetable waters distribution on soil dedicated to wheat and corn]. *L'informatore Agrario* 45:58–62.
61. Catalano, M., and M. De Felice. 1989. Utilizzazione delle acque reflue come fertilizzante [Use of olive-oil mill wastewater as fertilizer]. Proceedings of International Seminar on Olive Oil Mill Effluents Purification, Lecce, pp. 251–261.
62. Fair, G. M., J. C. Geyer, and D. A. Okun. 1968. *Water and Wastewater Engineering*. New York: Wiley & Sons.
63. Bianucci, G., and E. Bianucci. 1992. Il trattamento delle acque residue industriali e agricole [Agro-industry and agricultural wastewater treatment]. Hoepli, Milan pp. 316–318.
64. Sanna, M. 1982. Antinquinamento nelle industrie alimentari [Antipollution in food industry]. AEB, Brescia (I), pp. 207–224.
65. Masotti, L. 1991. *Depurazione delle acque* [Water Purification]. Bologna: Calderini.
66. Martinez-Nieto, L., S. E. Garrido-Hoyos, F. Camacho-Rubio, M. P. Garcia-Pareja, and A. Ramos-Cormenzana. 1993. The biological purification of waste products from olive oil extraction 43(3):215–219.

67. Giorgio, L., C. Andrezza, and G. Rotunno. 1981. Esperienze sul funzionamento di un impianto di depurazione per acque di scarico civili e di oleifici [Experimental trials on combined treatments of urban and olive mill effluents]. *Ingegneria Sanitaria* 5:296–315.
68. Boari, G., and I. M. Mancini. 1990. Combined treatments of urban and olive mill effluents in Apulia, Italy. *Water Science Technology* 22(6):235–240.
69. Mascolo, A., A. Cucurachi, L. di Giovacchino, and A. Ranalli. 1990. Disposal of waste water from olive oil production, by means of activated sludge plants for treatment of urban sewage. *Annali dell'Istituto Sperimentale per la Elaiotecnica* 9:107–120.
70. Hamdi, M. 1992. Toxicity and biodegradability of olive mill wastewaters in batch anaerobic digestion. *Applied Biochemistry and Biotechnology* 37(2):155–163.
71. Borja, R., A. Martin, R. Maestro, J. Alba, and J. A. Fiestas. 1992. Enhancement of the anaerobic digestion of olive mill wastewater by the removal of phenolic inhibitors. *Process-Biochemistry* 27(4):231–237.
72. Padilla, R. B., A. Martin, J. A. Fiestas, J. M. Olias, and M. M. Duran. 1992. Uso di sepiolite e bentonite per la degradazione di composti fenolici negli scarichi di oleifici [Use of sepiolite and bentonite for phenolic compound decay of olive oil mill effluents]. *Inquinamento* 3:114–117.
73. Hamdi, M., and J. L. Garcia. 1993. Anaerobic digestion of olive mill wastewaters after detoxification by prior culture of *Aspergillus niger*. *Process-Biochemistry* 28(3):155–159.
74. Hamdi, M., A. Brauman, and J. L. Garcia. 1992. Effect of an anaerobic bacterial consortium isolated from termites on the degradation of olive-mill waste-water. *Applied Microbiology and Biotechnology* 37:408–410.
75. Lettiga, G., and A. F. M. Van Velsen, S. W. Hobma, W. De Zeeuw, and A. Klapwijk. 1980. Use of the upflow sludge blanket (USB) reactor concept for biological wastewater treatment, especially for anaerobic treatment. *Biotech. Bioeng.* 22: 699–734.
76. Boari, G., A. Brunetti, R. Passino, and A. Rozzi. 1984. Anaerobic digestion of olive mill wastewater. *Agricultural Wastes* 10:161–175.
77. Fiestas, J. A., R. Navarro Gamero, R. L. Cabello, A. J. Garcia Buendia, and G. M. Maestojuan Saez de Jauregui. 1982. Depuración anaerobia del alpechin como fuente de energía [Anaerobic treatment of olive mill wastewater as energy source]. *Grasas y Aceites* 33:165–270.
78. Martin, A., R. Borja, I. Garcia, and J. A. Fiestas. 1991. Kinetics of methane production from olive mill wastewater. *Process-Biochemistry* 26(2):101–107.
79. Gavala, H. N., I. V. Skiadas, N. A. Bozinis, and G. Lyberatos. 1996. Anaerobic codigestion of agricultural industries wastewater. *Water Science Technology* 34(11): 67–75.
80. Borja, R., and A. Gonzalez. 1994. Comparison of anaerobic filter and anaerobic contact process for olive mill wastewater previously fermented with *Geotrichum candidum*. *Process-Biochemistry* 29(2):139–144.
81. Georgacakis, D., and D. Dalis. 1993. Controlled anaerobic digestion of settled olive-oil wastewater. *Bioresource-Technology* 46(3):221–226.

82. Annesini, M. C., A. R. Giona, F. Gironi, and F. Pochetti. 1983. Treatment of olive oil wastes by distillation. *Effluent and Water Treatment Journal* 23(6):245
83. Amirante, P., and G. C. Di Renzo. 1989. Impianti di concentrazione termica delle acque reflue [Concentration plants for olive oil mill effluents]. Proceedings of International Seminar on Olive Oil Mill Effluents Purification, Lecce, pp. 95–119.
84. Vigo, F., M. Giordani, and C. Campanelli. 1981. Ultrafiltrazione di acque di vegetazione dei frantoi di olive [Olive oil mill effluents ultrafiltration]. *Rivista Italiana delle Sostanze Grasse* 2:70–73
85. Vigo, F., M. De Paz, and L. Avalle. 1983. Ultrafiltrazione di acque di vegetazione di frantoi di Olive: Esperienza gestionale in impianto pilota. [Olive oil mill effluents ultrafiltration: Management experiences on a pilot plant]. *Rivista Italiana delle Sostanze Grasse* 5:267–271.
86. Massignan, L., P. De Leo, and C. Carrieri. 1985. Depurazione mediante osmosi inversa di acque reflue da oleifici [Purification of wastewater from olive oil mill, using reverse osmosis]. *Riv. Italiana di Scienze dell'Alimentazione* 14:421–428.
87. Amirante, P., and G. C. Di Renzo. 1989. Trattamenti di osmosi inversa e ultrafiltrazione [Reverse osmosis plants for olive oil mill effluents]. Proceedings of International Seminar on Olive Oil Mill Effluents Purification, Lecce, pp. 165–184.
88. Pieralisi, G. 1989. Impianti di concentrazione termica (Thermal concentration plants for OPE). Proceedings of International Seminar on Olive Oil Mill Effluents Purification, Lecce, pp. 121–145.
89. von Sperling, M. 1996. Comparison among the most frequently used system for waste water treatments in developing countries. *Water Science Technology* 33(3): 59–72.
90. Iannelli, G. 1974. Il costo degli impianti di depurazione [Cost of the wastewater treatment plants]. *Ingegneria Ambientale* 3:270–288.

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