PHYSICAL PROPERTIES OF PLANT AND ANIMAL MATERIALS

STRUCTURE, PHYSICAL CHARACTERISTICS AND MECHANICAL PROPERTIES

Nuri N. Mohsenin
Professor of Agricultural Engineering
The Pennsylvania State University

ROUTLEDGE

PHYSICAL PROPERTIES OF PLANT AND ANIMAL MATERIALS

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

PHYSICAL PROPERTIES OF PLANT AND ANIMAL MATERIALS

STRUCTURE, PHYSICAL CHARACTERISTICS AND MECHANICAL PROPERTIES

Nuri N. Mohsenin
Professor of Agricultural Engineering
The Pennsylvania State University

Routledge
Taylor & Francis Group
LONDON AND NEW YORK

First published 1970 by Gordon and Breach, Science Publishers, Inc.

Published 2019 by Routledge
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN
52 Vanderbilt Avenue, New York, NY 10017

Routledge is an imprint of the Taylor & Francis Group, an informa business

Library of Congress catalog card number 78-97180

ISBN 13: 978-0-677-02300-7 (hbk)

PREFACE

The increasing economic importance of food materials together with the complexity of modern technology for their production, handling, storage, processing, preservation, quality evaluation, distribution and marketing, and utilization demand a better knowledge of the significant physical properties of these materials. From the production units on the farm to the consumer, food materials are subjected to various physical treatments involving mechanical, thermal, electrical, optical, and sonic techniques and devices. It is essential to understand the physical laws governing the response of these biological materials so that the machines, processes, and handling operations can be designed for maximum efficiency and the highest quality of the end products. Maintenance of quality under adverse conditions of handling, storage and distribution, savings in weight and bulk in some cases, reduced costs in handling and processing operations, and finding new ways for utilization may result from an understanding of the basic physical properties of economic plant and animal materials.

Despite the importance of the subject, intensive research and study in this area have only started during recent years. In the past, however, considerable research has been reported in various scientific journals on physical properties and characteristics of biological materials particularly those of interest to the food and agricultural industries. This book which is the outgrowth of class notes prepared for teaching a course in this area, is an attempt to place the most significant research reports on physical characteristics and properties of plant and animal materials under one cover. The contents should be of value as text material for students and teachers as well as researchers in any branch of science and technology concerned with physical behavior of biological materials. Agricultural and food engineers, bioengineers, food, plant and animal scientists should find the book useful as a reference material.

The book contains topics of gross structure and terminology of the economic plant and animal materials, physical characteristics such as shape, size, volume, density, porosity, etc., and mechanical and rheological properties.

Emphasis is placed on fundamentals of engineering sciences as applied to biological materials for their characterization and determination of physical properties. Once the material has been characterized and a range for its various physical properties has been established, it is necessary to interpret the results in a form which would have engineering utility and implications. For this reason, when possible, examples have been given to illustrate the application of a certain property in design and analysis, utilization, and quality control.

Where tabulated data are needed for discussion, they are given in the main body of the text. Otherwise, the data on physical properties are given in tables in the Appendix. The symbols used are usually defined in the text. However, for ease of reference, a definition of symbols used in each chapter is also found at the end of that chapter.

Acknowledgment is due to Professor F. W. Peikert, Head, Department of Agricultural Engineering, and other colleagues for their encouragement in preparation of the manuscript. The writer sincerely appreciates the painstaking work of George Kann for preparation of many of the ink drawings and Shirley Brungart, Dorothy Olbricht, and Sue Brocail for typing of the multilith masters for the preliminary copies of this book printed in 1966 and 1968. The author is particularly indebted to C. T. Morrow for his continuous assistance in supplying references, conducting experiments, helping with class and laboratory instructions covering materials from this book, and reading the first draft of the manuscript. Other associates in particular, R. K. White, J. R. Hammerle, D. R. Bittner and Leora Shelef have also contributed to the compilation, checking and analysis of the data reported as unpublished work. The graduate students who have been associated with the author in research on physical properties of agricultural products over the past nine years have all contributed to this work through their theses, special assignments, or working of the problems. They are: D. R. Bittner, H. E. Cooper, D. G. Cowart, R. S. Devnani, R. G. Diener, J. Duru, E. E. Finney, W. F. Fletcher, J. J. Gaffney, J. R. Graham, J. R. Hammerle, C. T. Morrow, C. W. Nelson, R. K. White, J. D. Whitney, Y. M. Yang.

It would be impossible to name and acknowledge all organizations and individuals for their permission to make use of their published work and their cooperation in supplying the requested information and illustrative material. Throughout the book, however, an attempt has been made to indicate the sources of all materials used. The bibliographical references to these sources are given at the end of this book.

Obviously, a preliminary work of this nature cannot be without error and should stand considerable improvement. The author will much appreciate receiving any suggestions and criticisms as to the organization, condensation, inaccuracies of statements or illustrations and typographical errors.

University Park, Pennsylvania NURI N. MOHSENIN

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

CONTENTS

1

IMPORTANCE

MODERN AGRICULTURE has brought about the handling and processing of plant and animal materials by various means such as mechanical, thermal, electrical, optical and even sonic techniques and devices. Despite these ever increasing applications, little is known about the basic physical characteristics and properties of these materials. Specific heat and other thermal characteristics, electrical conductivity and dielectric constants, light transmittance characteristics, and such mechanical properties as stress–strain behavior, resistance to compression, impact and shear, and coefficient of friction are a few examples of these unknown properties. A knowledge of these properties should constitute important and essential engineering data in design of machines, structures, processes and controls; in analyzing and determining the efficiency of a machine or an operation; in developing new consumer products of plant or animal origins; and in evaluating and retaining the quality of the final product. Such basic information should be of value not only to engineers but also to food scientists and processors, plant and animal breeders, and other scientists who may exploit these properties and find new uses. To understand and appreciate the need for information on physical properties of plant and animal products, a few examples are given in the following.

1.1 PHYSICAL CHARACTERISTICS

Shape, size, volume, surface area, density, porosity, color and appearance are some of the physical characteristics which are important in many problems associated with design of a specific machine or analysis of the behavior of the product in handling of the material.

What shape is to be assumed for the material and which dimension is to be employed in calculations are two first questions which one must answer before analyzing the cooling curve of a fruit or understanding the problem of separation of seeds and grains from undesirable materials by pneumatic or electrostatic devices.

There are many charts available for solving the problems of transient heat flow in engineering materials. A glance at these charts shows that accurate estimates of the shape and the related dimensions of the material are necessary before the chart can be used in solution of the problem of heat transfer in the body in its natural state. As will be seen later the problem has been solved by either assuming a spherical shape for the product or confining a bulk of the material in a cylindrical container or a slab-shaped box before placing the product in the heating or cooling medium.

One of the important design parameters in conveying of solid materials by air or water is the assumption for the shape of the material. Accurate estimates of the frontal area and the related diameters are essential for determination of terminal velocity, drag coefficient, and Reynolds number.

Table 1.1 shows the assumptions made by several investigators in calculating aerodynamic characteristics of some agricultural products.

The question of shape and size is also important in problems of stress distribution in the material under load, in electrostatic separation of seeds and grains, in light reflectance and color evaluation, and in development of sizing and grading machinery.

A knowledge of density and specific gravity of agricultural products is needed in calculating thermal diffusivity in heat transfer problems, in determining Reynolds number in pneumatic and hydraulic handling of the material, in separating the product from undesirable materials and in predicting physical structure and chemical composition.

The irregular shape and porous nature of many agricultural products present difficult problems in volume and density measurements. Such simple techniques as water displacement can result in appreciable errors if the water can penetrate into the material or if the material is very small in size, such as small seeds. A difficult example in this area has been the density evaluation of an expanded forage wafer.

Surface color and appearance of agricultural products are valuable physical characteristics for selective separation in the field as subsequent handling and processing (Fig. 1.1). In selective harvesting of fruits and vegetables and in sorting and grading at post harvest and during storage,

Table 1.1 Frontal area and diameter assumed in investigating the aerodynamic characteristics of agricultural products

Material	Shape chosen	Diameter chosen	Frontal area	Reference
Seed grains	Ellipse	$\dfrac{L_1 + L_2 + L_3}{3}$	$\pi L_1 L_2/4$	Bilanski (1962)
Grains	Sphere	D	$\pi D^2/4$	Garrett and Brooker (1965)
Grass seeds	Sphere	d	$\pi d^2/4$	Keck and Goss (1965)
Fruits	Sphere	d_{ave}	$\pi d^2_{\text{ave}}/4$	Schmidt and Levin (1963)
Potatoes	—	—	measured (max.)	Gilfillan and Growther (1959)

L_1, L_2, L_3 = length, width, and depth, respectively

D = diameter of a sphere having volume equal to that of the grain (volume found from weight divided by specific weight)

d = diameter of a sphere found by taking the geometric mean of the 3 mutually perpendicular measured seed dimensions

d_{ave} = average of maximum and minimum diameters of the fruit

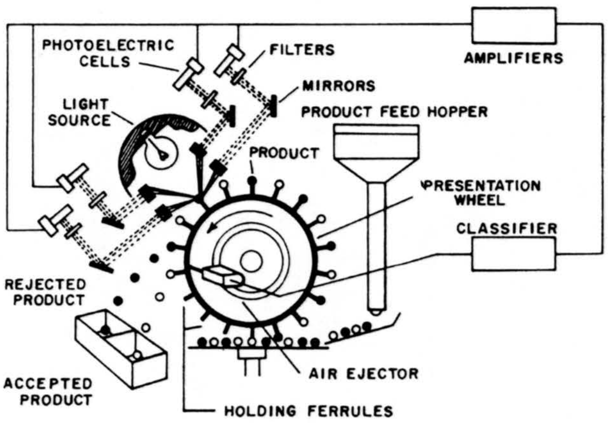


Figure 1.1 Application of light reflectance characteristics of agricultural Products in sorting and grading machines (courtesy Mandrel Industries, Inc.)

desirable products can be selected on the basis of color and appearance. Here the light reflectance characteristics of the product is the important physical property which must be known before equipment can be designed for separation and sorting or grading. However, irregular shape and non-uniform color of the object with certain reflectance characteristics which occur at only one or two narrow regions of the spectrum present problems which require special techniques and instrumentation.

1.2 MECHANICAL PROPERTIES

Mechanical Damage to seeds and grains which occur in harvesting, threshing, and handling can seriously affect viability and germination power, growth vigor, insects and fungi attack, and quality of the final product (Table 1.2). Depression of viability is due to mechanical damage to the embryo of the seed. The depression of growth vigor of the damaged seed has been demonstrated by the decrease of the size of shoots and of the weight of the plants (Fig. 1.2).

Table 1.2 Mechanical damage to wheat grain in threshing trials (King and Riddolls, 1959)

	Concave clearance, in.				Drum speed, rpm			
	1/8	5/32	3/16	7/32	1100	1000	900	800
Visible damage %	7.7	8.3	8.5	7.2	19.9	10.0	8.1	5.0
Germination of visibly undamaged seed %	90.4	89.9	90.6	90.9	78.7	88.0	92.6	92.6
Wastage %	16.0	16.9	16.8	15.2	36.9	20.9	14.9	11.9

Pea bean crackage has been a problem during handling in elevators. The amount of damage is apparently affected by temperature, moisture content and impact loading.

Hardness of grains has been a subject of interest to millers, livestock feeders, breeders and other agricultural scientists. Biting or cutting the grain has provided a qualitative evaluation of grain hardness. A number of attempts have been made to find an objective and a quantitative measure of the hardness of individual kernels or the average of a collection of kernels. The data are used to ascertain the relationship between hardness and certain physical and chemical properties, feeding value, and size reduction and milling characteristics of the grain.

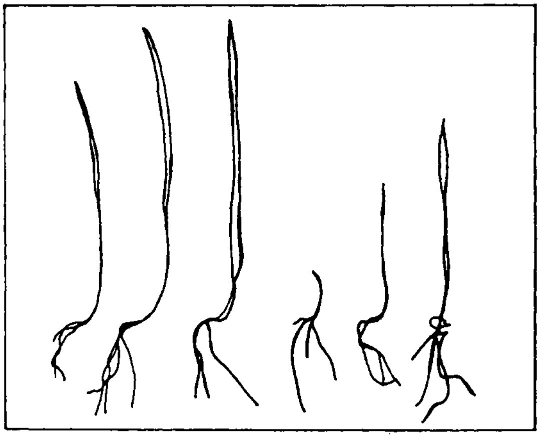


Figure 1.2 Mechanical damage to seeds causes depressed germination and growth vigour (Usenko, 1952)

Mechanical properties such as compressive strength, impact and shear resistance, are important and in some cases necessary engineering data in studying size reduction of cereal grains as well as seed resistance to cracking under harvesting and handling conditions (Fig. 1.3). From an energy standpoint, this information can be used to determine the best method (shear, impact or static crushing) to breakup or grind grain.

Static and sliding coefficients of friction of grains, forage materials, and some other farm products on metals, wood and other materials are needed by design engineers for rational design and predicting motion of the material in harvesting and handling equipment. Coefficient of friction is also important in determining the pressure of grain and silage against bin walls and silos. Compressibility, expansion characteristics, coefficients of internal friction and cohesion, and elasticity of forage or silage mass are important in studying compressibility of the material and determining methods of compressing and packaging (Fig. 1.4). Shearing resistance and bending strength of forage crops as they are cut are also important mechanical properties for under-

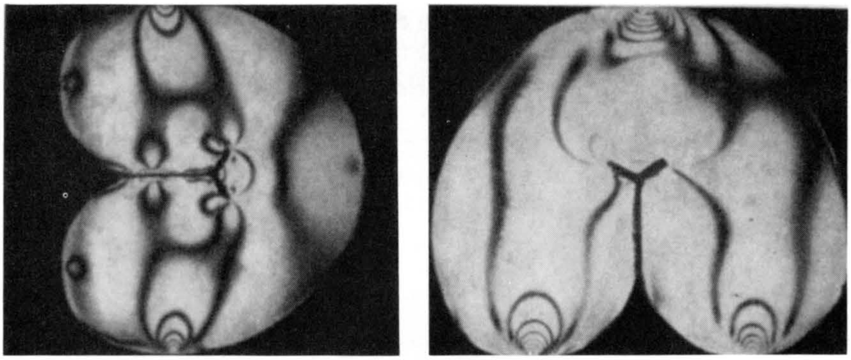


Figure 1.3 Photo-elastic techniques are employed to study mechanical damage in wheat grains (Arnold and Roberts, 1966)

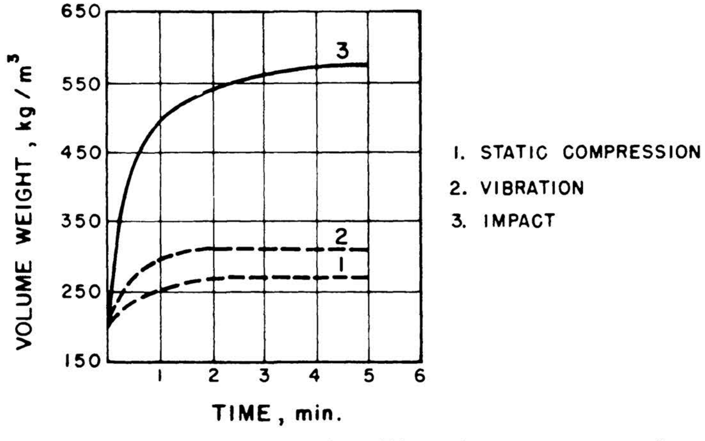


Figure 1.4 Under otherwise equal conditions, the greatest compression of silage has been obtained by impact compression (Yaremenko, 1956)

standing the nature of the cutting process and energy requirements in mowing machines.

Aerodynamic and hydrodynamic properties of agricultural products are needed for air and water conveying and separation of foreign materials. Density, size, shape, and drag coefficient are the physical properties needed in calculating the terminal velocity of an object in the fluid. In air conveying or pneumatic separation, an air velocity greater than terminal velocity would lift the particle. To allow the particle to fall gently, the air velocity is adjusted to a point just below the terminal velocity.

Mechanical harvesting, bulk handling, transporting, and storage of fruit and vegetable products have also indicated a need for basic information in mechanical properties. Bruising and skinning of mechanically harvested potatoes, distortion of union bulbs in bottom of the storage pile, and mechanical damage to fruits and vegetables by compression, impact, and vibration have lowered the grade of these products, with consequent loss to the grower (Fig. 1.5, 1.6).

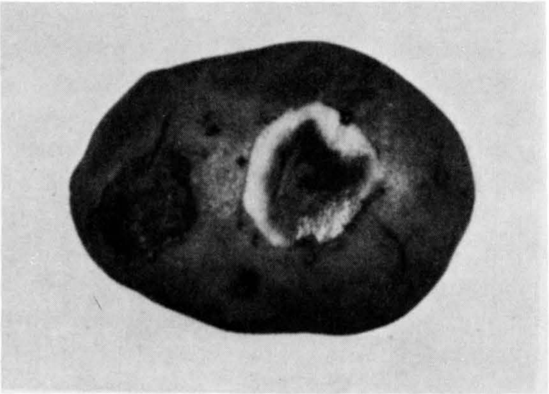


Figure 1.5 Dead loads experienced by potato in storage piles causes mechanical damage (courtesy C. H. Green, NIAE, England)

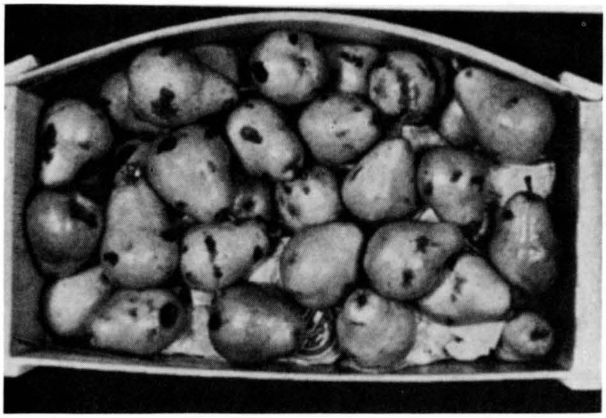


Figure 1.6 Mechanical damage to pears due to in-transit vibration (O'brien, 1965)

If mechanical handling of agricultural products results in deformation and flow of the materials, the mechanical properties involved will be referred to in this work as rheological properties. On the basis of this definition, many of the preceding examples involve deformation and flow and thus concern the rheological properties. Additional examples of rheological properties are such textural attributes of food products (Fig. 1.7) as firmness, yielding quality, crispness, fibrousness and such flow characteristics as viscosity, consistency, and fluidity of liquid feed and waste materials handled in slurries.

1.3 THERMAL PROPERTIES

Many of the agricultural products of plant or animal origin are subjected to various types of thermal processing before they are placed at the access of the consumer. The thermal processing may include heating, cooling, drying, and freezing. It is upon the thermal properties of the product that any change of temperature will largely depend.

Hard seed of alfalfa and red clover can be made permeable by application of properly regulated heat. Heating of these seeds for four minutes at 220°F. has reduced the munber of hard seeds by as much as 80 per cent. Specific heat of seeds is an important physical property in heat treating applications where germination and viability of seeds may be endangered if critical temperature or time of heating is exceeded.

Heat treatment of wheat, corn, and legumes has shown some promise in stimulating germination. Enzymes in cotton seed can be completely inactivated by dielectric heating, thus preventing seed spoilage while in storage. The fungus causing the decay of onions in storage vanishes in the temperature range of 40° to 60 °C (Gasnikow, 1960). Heat treatment of peaches has shown promise in delaying the decay of the fruit in storage and improving the quality retention.

In fruits and vegetables the action of enzymes and microorganisms causing deterioration can be controlled by low temperature. It is said that fresh produce deteriorate as much in an hour at 90°F. as in a day at 50°F. or in a week at 32°F. Guillou, 1958). To cool the fresh fruit as rapidly as possible, a "portable harvest cooler" has been developed which can be hauled right out to the orchard.

Heating or cooling of agricultural products may be accomplished by the

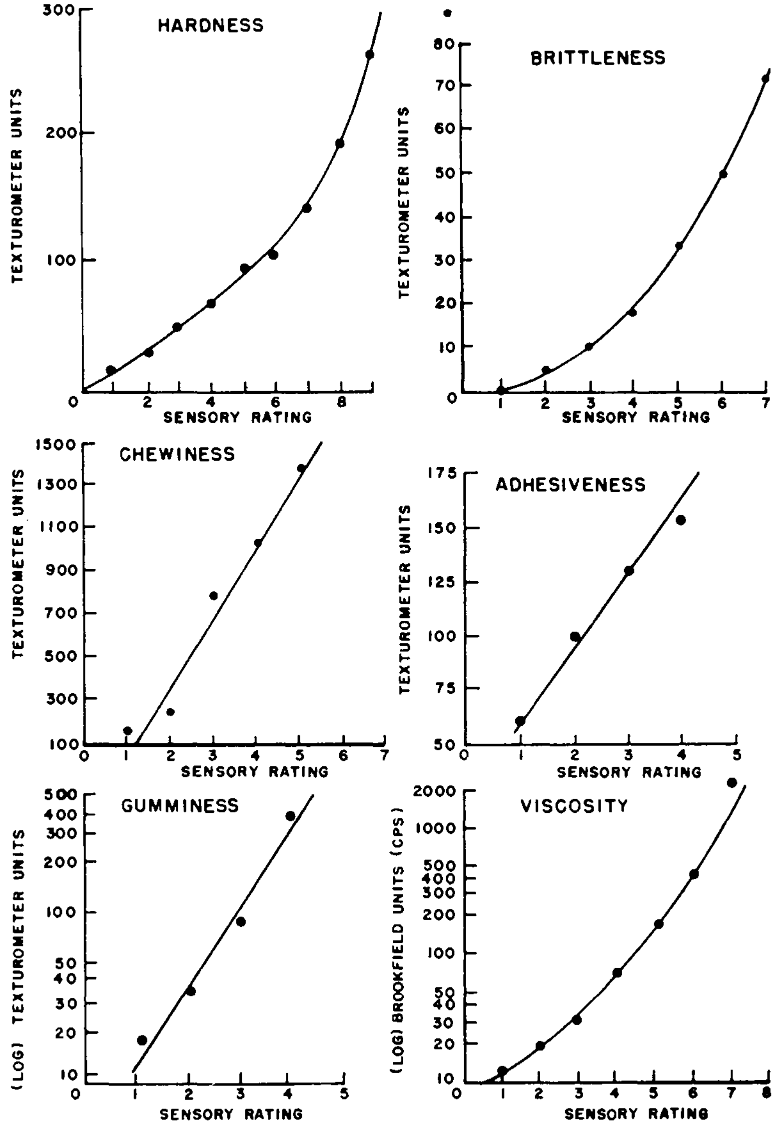


Figure 1.7 Mechanical parameters are the most important attributes in texture evaluation of food products (Szczesniak *et al.*, 1963)

methods of convection, conduction and radiation. A knowledge of such thermal characteristics as specific heat, thermal conductivity, thermal diffusivity surface conductance, and emissivity as well as such physical characteristics as density, shape and size is essential for design of the equipment and predicting of the processes. A heat balance for a heating or cooling system cannot be attempted without a knowledge of the heat capacity of the material. To define the magnitude and location of a temperature that denotes the heat content of the material at any time during a heating or cooling process, a knowledge of the thermal characteristics of the material is required. In heat treatment of steel, a desired microstructure can be obtained by controlling the time and temperature of heating. In heat treatment of biological materials, time and temperature are equally important if viability, nutrients and quality of the material are to be preserved.

1.4 ELECTRICAL PROPERTIES

Some electrical properties of agricultural products which are important in handling and processing are electrical conductance and capacitance, dielectric properties, and reaction to electromagnetic radiation.

Electrical conductance or capacitance properties have been used in moisture content determination of products such as cereal grains. Electrical resistance methods have been employed for precise measurement of cotton fiber length distribution and fineness of wool fiber.

The principle of electrostatic separation which has been known for centuries is being investigated for separation and cleaning of agricultural seeds (Fig. 1.8). With small seeds, it has been found that electrostatic separation is essentially independent of size, shape, weight, and surface texture. When devices depending upon these physical characteristics fail to separate similar seed varieties, the seed's ability to hold electrostatic charge can be used for separation. Conductivity of the seed is the property which would determine, basically, the ability of the seed to hold surface charge.

An impedance technique can be used to determine the extent of injury to plant tissues due to frost, poisoning by spray, or other means of damage, This technique is based on the fact that when a tissue is dead it has no capacitance and when it is uninjured and healthy, has resistance and capacitance comprising an impedance. Thus the ratio of lowfrequency impedance to high-frequency impedance, measured with a wide-range a. c. bridge, is an indication of the degree of injury to the plant tissue.

Dielectric heating, which is the heating of the material due to its own dielectric losses when placed in an electrodynamic field, has been used quite extensively in drying plastics, ceramics and other nonconducting materials. Uniformity of heating and the high rates of temperature rise are two principal advantages which make dielectric heating attractive for heat treatment and drying of agricultural products (Fig. 1.9). The possibilities of dielectric heating have been investigated for inactivating the enzymes in cotton seed, controlling insects and fungi in seeds, and drying rice and other grains. The use of high-frequency electric field to cotton seeds have shown that the enzymes in the seed could be completely inactivated in six minutes. Further, it was found that during and after the treatment, drying of the cotton seed took place which further improved the quality for storage. Dielectric heating has also been used in heat treatment of seeds. Using the correct amount of exposure to radio-frequency electric fields, germination and early growth was stimulated while some dormant or hard seeds were made immediately germinative.

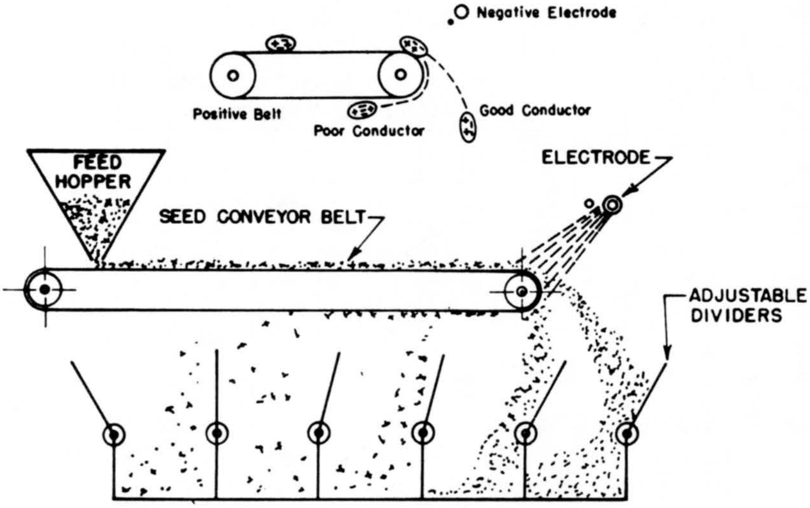


Figure 1.8 Ability of seeds to conduct an electrical charge can be used for seed cleaning by electrostatic separation (Harmond *et al.*, 1961)

Electromagnetic radiation has considerable potential for processing of agricultural products. Scientists have found many practical applications for any of the several ranges of radiation in the electromagnetic spectrum (radio-frequency, infrared, visible, ultraviolet, x-rays, and gamma rays). The principal effects of radiation can be divided into 1) the heating effects (longer wave length and lower energy range) and 2) chemical effects (shorter wave length and higher energy range) causing ionization of the atoms. Certain physical properties of agricultural products would probably be important in determining their reactions to electromagnetic radiations.

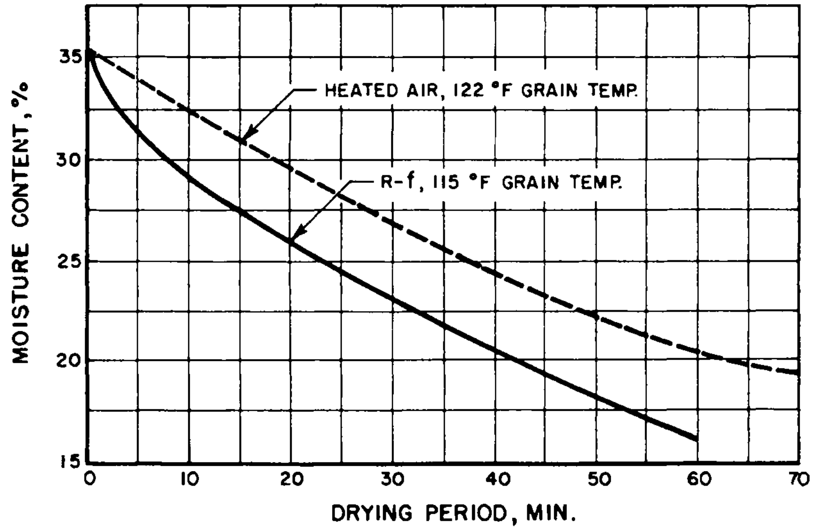


Figure 1.9 Grain drying by radio-frequency (R-f) heating results in faster and more uniform heating of the grain. Comparison with heated air drying requires a knowledge of dielectric properties of the grain (Knipper, 1956)

1.5 OPTICAL PROPERTIES

Light transmittance and reflectance properties of agricultural products have been explored in recent years for electronic sorting and grading, maturity, and surface color determinations, and study of the interior characteristics of fruits and vegetables.

From an optical point of view intact agricultural products are dense, light scattering materials which require a highly sensitive and specially designed spectrophotometer for measuring their spectral transmittance characteristics.

An instrument has been developed which allows the transmittance and measurement of monochromatic light through intact biological specimens (Norris, 1958). The technique, which is based on light transmittance characteristics and absorption spectra of the material has been exploited to determine internal color of tomatoes, smut content of wheat, fruit maturity, degree of milling of rice, internal discoloration of potatoes, blood spots and green rot in eggs, water core in apples, insect infestation in wheat, moisture content of seeds, scald damage in cherries, and damage in yellow corn (Fig. 1.10, 1.11).

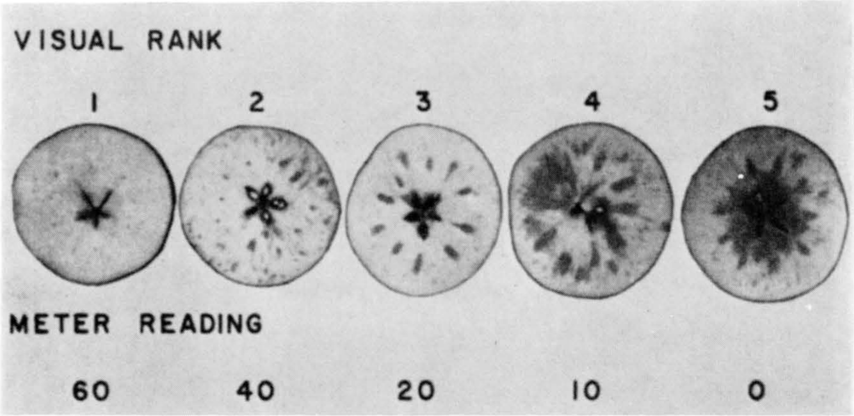


Figure 1.10 Presence of water core in apples can be found non-destructively by light transmittance (courtesy USDA Instrumentation Research Laboratory, Beltsville, Maryland)

Several workers have considered the light reflectance characteristics of agricultural products for selecting, grading, and separation of desirable products from foreign materials. The reflectamce properties of potatoes were found sufficiently different from those of soil clods to suggest that reflectance may be used to differentiate between the two materials electronically (Palmer, 1961). The sorting efficiency of workers in cherry processing plants as affected by the spectral distribution of the illuminating light as well as the reflectance of cherries and their defects has been investigated (Parker and Wiant, 1954). Light reflectance curves of lemons have shown distinct variation in various stages of fruit maturity. The use of this principle has been explored for the design of a color sorting machine (Powers, *et al.*, 1953).

Figure 1.11 An experimental fruit sorting machine employing principles of light transmittance (Yeatman and Norris, 1965)

2

STRUCTURE AND RETENTION OF WATER

STUDY OF PHYSICAL properties of materials from plant or animal origin requires some knowledge of their structure as well as certain physiological activities influencing these properties. In this chapter we will discuss briefly only those aspects of structure which have direct bearing on the physical properties of selected economic plant and animal materials. For further information in the structure and physiology of these materials the reader is referred to the selected list of references compiled for this chapter. A portion of this discussion is devoted to the absorption and desorption of moisture because the physical properties are highly dependent on the moisture content of the material.

2.1 ORGANIZATION OF THE PLANT BODY

The plant body consists of structural units called cells. Each cell is enclosed in its own cell wall and united with other cells by means of a cementing substance. Cells are then grouped together to form *tissues* which may be classified as protective tissues, conductive tissues, and ground tissues.

The *protective tissues* are composed of guard cells to protect the organ from mechanical injury, insects, fungi, microorganisms and control the transpiration and aeration in the tissue system. They include the *epidermis* and *periderm* tissues which are the primary and the secondary outer protective covering of the plant body (Fig. 2.1). The protective cells are closely pressed together and are usually quite tough. Epidermis of fresh produce usually contain minute valves, called stomata, for exchange of gases. Also cutinization of the outer walls of these cells make them impervious to water.

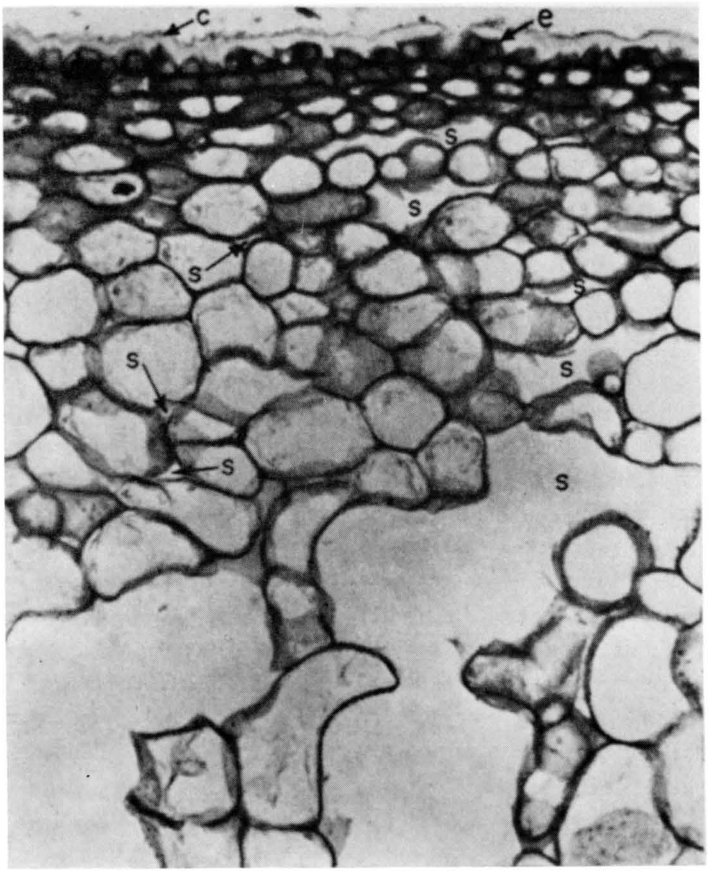


Figure 2.1 Transition from skin to flesh parenchyma in Granny Smith apples, X150: c—cuticle, e—epidermis, s—intercellular space (Reeve, 1953)

Cutin is a layer of waxy material which usually presents problems in mechanical testing, when one attempts to use epoxy resins or other bonding agents on the surface of the intact specimen.

The *conducting or vascular tissues* contain the *phloem* (food conduction) and the *xylem* (water conduction) tissues (Fig. 2.2). The cells are composed of long tubes with their walls made of primarily cellulose and sometimes lignin forming the fibrous material which contributes to stringiness and toughness in some food materials. This part of the structure of conducting tissues may also be classified as supporting tissues.

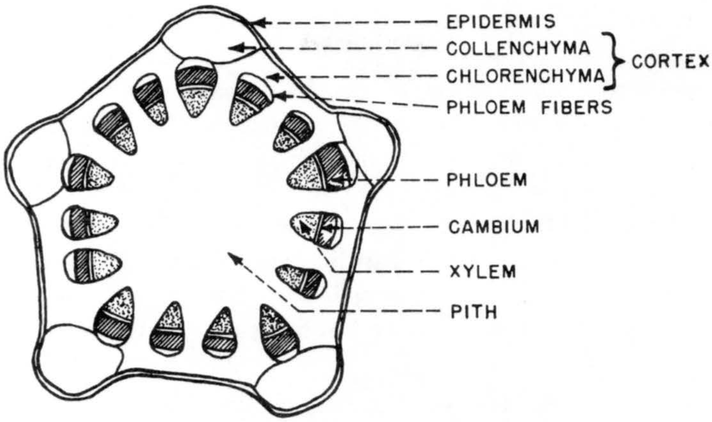


Figure 2.2 Schematic diagram of a young alfalfa stem

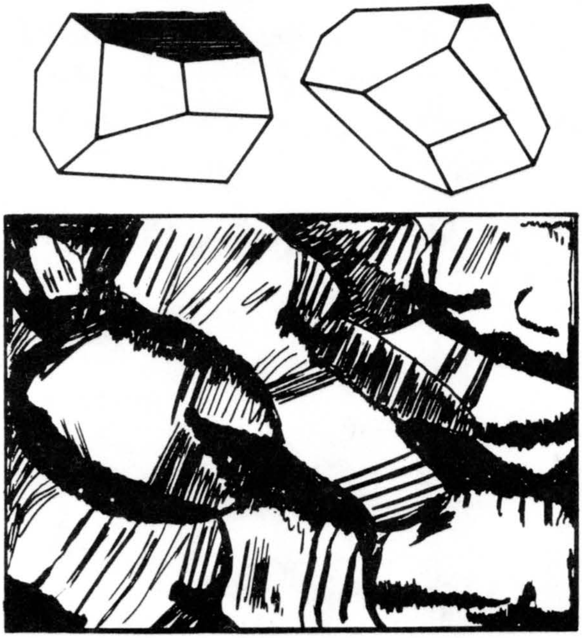


Figure 2.3 Parenchyma cells in edible portion of fruits and vegetables. Above: polygonal shape of the cells. Below: intercellular air shown in dark shadows (Meyer, 1960)

The *ground or supporting tissues* are the parenchyma, the collenchyma, and the sclerenchyma tissues. The *parenchyma* cells are the chief type of cells in plant materials appearing in various special forms as the structural units in most of the other parts of the plant body. The parenchyma cells are large, thin-walled and polygonal in shape as shown in Fig. 2.3. The internal structure of parenchyma cells (Fig. 2.4) may contain plastids or may be adapted for the storage of water and reserve foods such as starch. They are living cells, capable of growth and division, and form the bulk of the primary tissues in plant materials and edible portions in fruits and vegetables. The parenchyma cells do not fit tightly together and are often

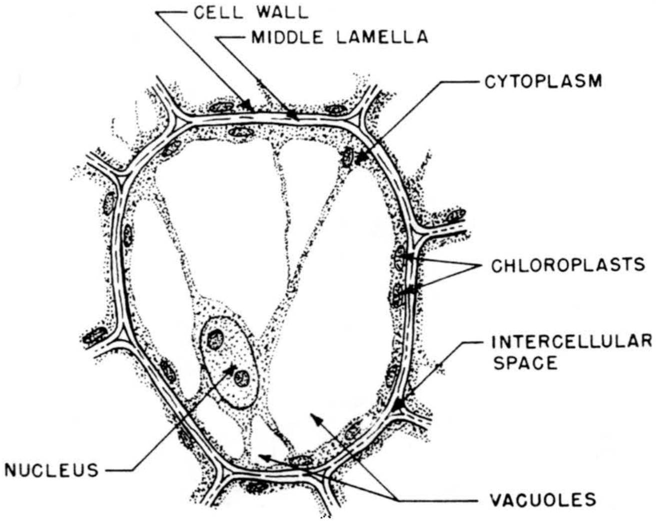


Figure 2.4 Structure and contents of a parenchyma cell (Brook, 1964)

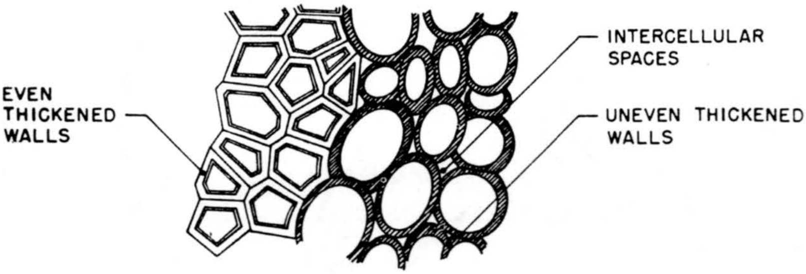


Figure 2.5 Collenchyma tissue (right) and sclerenchyma tissue (left) provide strenght and mechanical support (Braungart and Arnett, 1962)

separated by intercellular spaces which may be filled with air or water and constitute as much as 25 per cent of total volume of the tissue in such fruits as apple (Table 2.3). The cementing agent, which may be pectic substances, lignin or other compounds at the middle lamella, hold these cells together to form the parenchyma tissues.

Collenchyma and *sclerenchyma* tissues provide strength and mechanical support for the plant body (Fig. 2.5). The cells in the former are a modified version of parenchyma cells (uneven thickened wall) and are the strengthening tissues in young plant materials. The latter are strengthening elements in mature plant parts with long slender cells distinguished as fiber cells (Fig. 2.6).

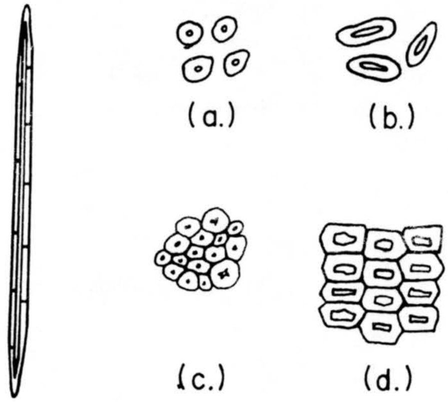


Figure 2.6 Single fibre cell (left) and cross-section of fibre cells in cotton (a), ramie (b), flax (c), and spruce wood (d) (a, b, c, d from Frey-Wyssling, 1952)

2.2 THE CELL WALL

It is generally agreed that mechanical properties of cell walls in plant materials reflect the mechanical properties of the plant tissues (Falk *et al.*, 1958; Frey-Wyssling, 1952). The elasticity, strength and rigidity of plant tissues, for example, are due to rheological properties of the cell wall (Frey-Wyssling, 1952). These cell walls are composed essentially of *cellulose microfibrils* embedded in an amorphous matrix. The microfibrils are relatively inert but their number and arrangement are largely responsible for the form and structural mechanics of the cell wall. Matrix materials also contribute to structure but are generally considered more reactive than the microfibrils and have been assumed to control rigidity in the cell wall.

The microfibrils are the real morphological units in the structure of a plant material. Similar fibrillar elements have been found in proteins. Figure 2.7 shows the fibrillar structure of natural cellulose fibre. Greater details of microfibrils are shown in Fig. 2.8 for a ramie fibre. The microfibrils of all cellulosic cell walls have about the same diameter (250–300 A°) and structure (Frey-Wyssling, 1952). They consist of some 25 *micellar strands* with about 2500 cellulose chains. However, the arrangement of the microfibrils is not equal in all cell walls. Furthermore, the crystallinity of the cell walls may be limited to the homogeneous crystal lattice within the micellar strands. The fraction of the amorphous cellulose holding these regions together may reach as much as 30 per cent (Frey-Wyssling, 1952). These areas of crystallization and amorphous cellulose have been studied by x-ray techniques. It is in the amorphous portions of the microfibrils that

Figure 2.7 Fibrillar structure of natural cellulose fibre; dark regions represent intercellular spaces (Meredith, 1956)

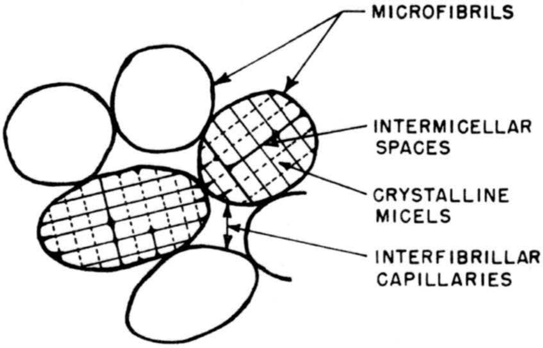


Figure 2.8 Cross-section of microfibrils in ramie fibre (Frey-Wyssling, 1952)

water absorption and swelling takes place. Also this part of the cellulose is believed to be flexible and capable of distortion without breaking. This property gives strength to plant tissues without rendering them rigid.

While the microfibrilar component of the cell wall consists basically of cellulose, the amorphous matrix component of the wall is composed predominantly of semicellulose and pectic substances (Setterfield and Bayley, 1961).

Semicellulose is an alkali-soluble, nonfibrous compound which is not very well defined. It is found mostly in wood but its presence in alfalfa hay, sugar cane, cornstalk, oat hulls and other agricultural materials has been reported (Meyer, 1960).

Pectic substances are basically straight chain polymers of considerable interest in foods of plant origin, particularly fruits and vegetables. In young plant materials pectic substances are in the form of protopectin which is water-insoluble. Upon aging, the water-insoluble protopectin changes to water-soluble pectin capable of forming gels with sugar and acid under

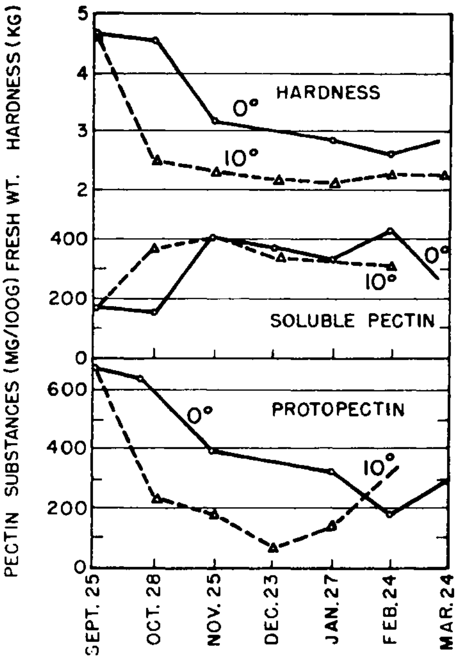


Figure 2.9 Changes in tissue firmness of canada apple as influenced by pectic substances (Meyer, 1960)

suitable conditions. The "mealiness" of over-ripe fruits is said to be partly attributed to this change in pectic substances. Figure 2.9 shows the changes in hardness of apples accompanying the changes of water-insoluble protopectin to water-soluble pectin. Note the fall of protopectin and the rise of water-soluble pectin until late in the storage period when a reversal of this trend occurs.

Although the exact location of pectic substances in a tissue is still a subject of dispute, it is agreed that they occur in the *middle lamella* between cells, acting as part of the cementing agent, as well as in the cell wall. In older plant materials, the cementing agent may, in addition to pectic substances, contain *lignin*. The presence of lignin together with thickening of cellulose layer in cell walls render the plant material woody and tough.

2.3 THE CELL CONTENTS

Within the cell wall is the *protoplasm* differentiated into various regions of cytoplasm, nucleus, and various inclusions (Fig. 2.4). The *cytoplasm* constitutes the main mass of the protoplasm with such rheological properties as non-Newtonian viscous behavior, elasticity, swelling and shrinkage, a measurable rigidity even though a fluid, and tensile strength. The *nucleus* directs much of the activity of the living cell including cell division, cellular metabolism and transmitting the heritable characters of the organism. The various inclusions in the protoplasm include numerous small bodies called *plastids*, such as chloroplasts important in the process of photosynthesis, and *vacuoles*, made up of droplets of solutions referred to as the "*cell sap*." In young plants, the vacuoles are small and numerous. As the cell grows older, the size of the vacuoles increase and join together to form often only one large vacuole in a mature cell. While the elasticity of the cell walls is recognized as the main factor responsible for elasticity of tissues, the cell sap is responsible for exerting a pressure called "*turgor pressure*" on the cell walls and keeping them in a state of elastic stress. The combined effects of this hydrostatic pressure (turgor pressure) of the cell contents with the elastic cell walls determine the viscoelastic properties of the tissues in the biological material. The effect of turgor pressure on stress and strain in the walls of the cells with simple geometric shape is discussed by Frey-Wyssling.

2.4 RELATIONSHIP BETWEEN TURGOR PRESSURE AND TISSUE RIGIDITY

The cellular structure of biological materials is such that it would be difficult to deduce the rheological properties of the whole material from the properties of the structural units, namely the cells. Even a simple uni-directional stress has to be transmitted through an irregular network of intercellular spaces and a random cellular arrangement. However, by assuming some simple and idealistic cellular models, it has been possible to explain certain relationships related to mechanical properties of tissues.

Nilsson and his co-workers (Nilsson *et al.*, 1958) showed that the dependence of elastic modulus in potato tissue upon turgor pressure in the cells, found experimentally, can be explained by a simple model in which the liquid-filled cells are assumed to be bounded by their elastic membranes. If all cells were spherical with radius r, the cell structure could be represented by Fig. 2.10 where in the cubical packing each sphere is assumed to be in contact with six neighboring cells. It is further assumed that the turgor pressure is equal in all cells of the model; the cell fluid cannot penetrate the cell walls while the tissue is being stretched; the cell walls are homogeneous, isotropic and elastic following the Hooke's law; and in the absence of external forces, all cell walls are free from internal stresses when the turgor pressure of the cell fluid is zero.

With these assumptions, the theory of elastic membrane was applied to derive the following linear relationship between the elastic modulus, E, of the plant tissue and the turgor pressure, p, in the cell fluid.

$$E = 3.6p + 2.5 \times 10^7 \text{ dynes/cm}^2$$

When the more realistic cell structure (isodiametric polyhedra) was considered in the analysis, it was found that the elastic modulus was only slightly sensitive to the assumed cell form and to the direction of the applied force (Fig. 2.10).

Experimental data (Falk *et al.*, 1958) has shown good agreement with theoretical results. Elastic modulus of the tissue was obtained by determining the elastic stretching of a specimen under a given force. The specimens were brought to osmotic equilibrium in solutions of different concentrations of mannitol and then taken out and dipped in paraffin oil to prevent osmotic changes during the modulus determinations. Turgor pressure was obtained by taking the difference between the osmotic value of the cell contents and that of the surrounding solution. Since the change in length of the cell is the same in all directions (isotropic cell wall), the change of volume can be calculated from the change in length and the osmotic value of the cell contents calculated using the Boyle–van't Hoff law (Tamiya, 1938).

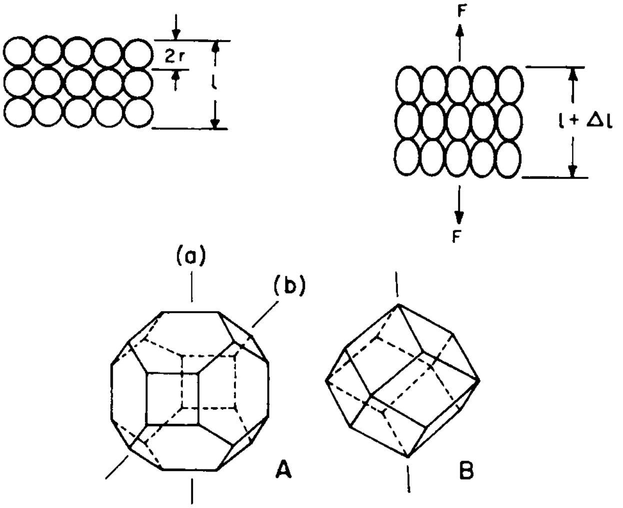


Figure 2.10 Top: The simplified model of potato parenchyma assumed in deriving the relationship between rigidity and turgor pressure. The more realistic form of the cell structure shown below showed little difference in the calculated elastic modulus (Nilsson, 1958)

2.5 DIMENSIONAL CHARACTERISTICS OF CELLS AND INTERCELLULAR SPACES

Information on size, shape and volume of the cells and the physical nature and characteristics of the intercellular spaces is often necessary for understanding the mechanism of flow and deformation and for interpreting the experimental data on mechanical and rheological properties. Such information can be found in source materials on plant physiology or periodicals concerned with specific commodities such as "Cereal Chemistry", "Tobacco Science," "American Potato Journal," etc.

The following information (Tables 2.1 through 2.5 and Fig. 2.11 and 2.12) gathered for apple fruits is presented here as examples of the type of data which may be found in the literature. Cell measurements were made on parenchyma tissues histologically prepared from the flesh of the fruit.

Estimation of volume of average cell, and cell wall surface were based on average diameter of cells measured microscopically with a calibrated eyepiece micrometer. The estimation was based on the assumption that the 14-sided parenchyma cells are nearly spherical. The total intercellular space per unit volume of tissue was made by vacuum infiltration of the tissue submerged in water. Knowing the percentage of intercellular space, the volume of the tissue actually occupied by cells was obtained as a percentage of total tissue volume. In determining this volume it was assumed that

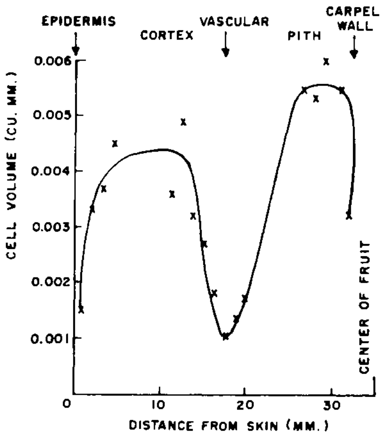


Figure 2.11 Gradient in cell volumes along an equatorial radius in a mature apple (Bain, 1951)

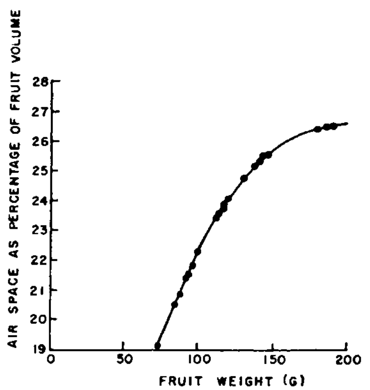


Figure 2.12 Relationship between air space and fruit weight in Granny Smith apples (Bain, 1951)

Table 2.1 Dimensions (in microns) of parenchyma cells in different tissue regions of apples (Reeve, 1953)

Variety	Skin	Outer flesh 1/8″–1/4″ (depth)	Inner flesh 3/8″–5/8″ (depth)	Core (length)	Core (width)
	Av SD	Av SD	Av SD	Av SD	Av SD
Newtown Pippin	76 ± 16	182 ± 42	210 ± 39	261 ± 58	136 ± 29
Winesap	67 ± 21	194 ± 42	214 ± 35	266 ± 42	142 ± 33
Delicious	67 ± 18	161 ± 27	170 ± 30	266 ± 57	124 ± 25
Rome Beauty	67 ± 24	193 ± 34	207 ± 29	327 ± 72	142 ± 21
Gravenstein	85 ± 27	221 ± 43	235 ± 58	494 ± 95	157 ± 32

Av = average
SD = standard deviation

Table 2.2 Dimensions (in microns) of intercellular spaces of middle flesh region of different apples (Reeve, 1953)

Variety	Width Av SD	Length Av SD	Greatest lengths observed
Delicious	269 ± 93	487 ± 154	1,000
Newtown Pippin	257 ± 72	485 ± 192	1,200
Winesap	275 ± 74	480 ± 157	1,200
Ripe Gravenstein	350 ± 108	665 ± 274	1,500
Rome Beauty	257 ± 75	562 ± 231	1,800
McIntosh	300 ± 75	590 ± 250	2,000

Table 2.3 Amount of intercellular space in different tissue regions of apples (Reeve, 1953)

Variety and character of fruit	Per cent of tissue occupied by intercellular space as determined by vacuum infiltration with water		
	Calyx-end flesh	Stem-end flesh	Middle portion of flesh
Delicious, ripe, not mealy	15	18.0	21.0—22.0
Gravenstein, ripe	17.6	20.1	25.4—27.0
Newtown Pippin, ripe	13.8—14.2	16.5	21.5—23.6
Rome Beauty, ripe	13.8	17.9	22.0—23.6
Winesap, ripe	15.3	17.7	19.8—20.7

Table 2.4 Size and number of cells and cell wall surface per unit volume of apple flesh parenchyma (Reeve, 1953)

Variety and tissue	Average cell diameter (microns)	Average wall area per cell (microns)^2	Average cell volume (microns)^3	Approx. per cent occupied by cells	Cells per unit volume (1 cc.)	Total surface of cell wall area per unit volume (1 cc.) (microns)^2
Newtown pippin						
Outer flesh	182	1.04×10^5	3.16×10^6	80	2.53×10^5	2.64×10^{10}
Inner flesh	210	1.39×10^5	4.85×10^6	80	1.65×10^5	2.3×10^{10}
Delicious						
Outer flesh	161	0.814×10^5	2.19×10^6	80	3.66×10^5	2.99×10^{20}
Inner flesh	170	0.91×10^5	2.57×10^6	80	3.11×10^5	2.83×10^{10}
Gravenstein						
Outer flesh	221	1.53×10^5	5.65×10^6	75	1.32×10^5	2.03×10^{10}
Inner flesh	235	1.73×10^5	6.8×10^6	75	1.1×10^5	1.9×10^{10}
Rome beauty						
Outer flesh	193	1.17×10^5	3.71×10^6	78	2.11×10^5	2.47×10^{10}
Inner flesh	207	1.35×10^5	4.6×10^6	78	1.69×10^5	2.29×10^{10}
Winesap						
Outer flesh	194	1.19×10^5	3.8×10^6	80	2.10×10^5	2.50×10^{10}
Inner flesh	214	1.44×10^5	5.13×10^6	80	1.56×10^5	2.24×10^{10}

Table 2.5 Relationship between cell number, cell volume and weight of Australian apple variety Granny Smith 149 days after full blossom (Bain, 1951)

Weight of fruit (g.)	Volume of tissue (cc.)	Mean cell volume (cu.mm. × 10^4	Cell number (× 10^{-6})
142.02	129	36	35.9
161.51	147	48	30.6
161.41	146	38	38.5
163.10	148	39	38.0
167.46	152	39	39.0
172.31	156	37	42.2
174.15	158	39	40.5
177.50	162	36	45.0
180.20	164	47	34.9
185.14	168	34	49.5
188.20	171	40	42.7
189.50	173	36	48.0
200.10	182	39	46.7
201.07	183	45	40.7
202.85	185	32	57.9
205.72	187	43	43.5
222.10	202	34	59.5
229.16	217	33	65.7
249.91	297	40	56.5

spheres of cells packed into the volume have no intercellular spaces. Models approaching this condition have been constructed with foam bubbles or by compressing soft lead shot in a steel cylinder (Marvin, 1939).

2.6 GROSS STRUCTURE AND CHEMICAL COMPOSITION OF SELECTED AGRICULTURAL PRODUCTS

For the benefit of the readers who are unfamiliar with the morphology and nomenclature of natural food materials, the gross structure and nomenclature for selected agricultural products are presented at the end of this chapter.

This descriptive nomenclature is followed by a table summarizing the constituents of selected food materials which should be helpful in understanding the physical behavior of the product. In this table water content values are on the wet basis, obtained by drying in vacuum at 100°C. The term "protein" is generally considered to be total nitrogen times the factor 6.25. Fat and oil content determination is based on the ether extract method. Nitrogen-free extract represents the so called "carbohydrates" such as starch, sugars, dextrins, and some unknown substances. Sugar and starch have also been reported separately. Acids, though widely removed from carbohydrates, are also included in nitrogen-free extracts. Ash is assumed to contain all of the mineral constituents.

2.7 RETENTION OF WATER IN BIOLOGICAL MATERIALS

The moisture content of agricultural products of plant origin exerts a profound influence on their physical properties. This influence is of major concern in proper storage, handling and processing of these materials.

Moisture is held in biological materials by two different mechanisms: *molecular adsorption* and *capillary absorption*. Molecular adsorption occurs when the water molecules adhere to specific points in the molecular structure of the material. When the distance between the water molecule and the cell wall becomes small enough (of the order of 10^{-7} cm), the force of attraction is large enough to draw the water into the micellar network of the cell wall (Barkas, 1953). The force of attraction at low moisture contents is so high that an "adsorption compression" results in a net decrease in volume of the solid–water aggregate.

As the moisture content increases, the molecular attraction becomes smaller and there is a volume increase which is roughly equal to the volume of water added. Due to the initial adsorption compression, however, the total volume of the aggregate remains smaller than that of constituents. The molecular adsorption is considered the primary cause of swelling in hygroscopic solids. The extent and the nature of the surface on which adsorption compression can take place appear to be the prime factor in molecular adsorption (Stamm and Seborg, 1935). The starch in corn kernel, for example, contains more polar sites for attraction of water molecules than does the cellulose (Chung, 1966). This should allow a larger amount of moisture to be adsorbed by starchy materials than cellulosic material.

At still higher moisture contents, where the vapor pressure has not yet reached the saturation point, most of the available points of attraction have been filled with water and further holding of water molecules is possible only through the formation of chains of water molecules or "water bridges" extending between those molecules which have been directly adsorbed. A direct tensile stress within the elastic limit of the material tends to rupture these water bridges. Removal of the stress can cause the water bridges to reform without any sign of plastic deformation. In the case of wood, it is claimed that when a shear stress is acting between parallel cellulose chains, the water molecules can jump from one point of attraction to another, resulting in some energy loss and plastic deformation in the material (Barkas, 1953). As there is no evidence that plasticity in wood has its origin in a slipping of entire cells over one another, this theory of inelastic jump of water molecules has been offered as the most plausible explanation for the increasing of plasticity in cellulosic materials with increasing moisture content (Glasstone *et al.*, 1941.)

Capillary absorption occurs when voids in the cellular structure are of the size to hold water in liquid form by forces of surface tension. The size of capillaries that will fill with water under different relative humidities can be calculated by the Kelvin equation given below

$$r = \frac{2\sigma M}{\varrho RT \ln (P_0/P)} \tag{2.1}$$

where

r = capillary radius
σ = surface tension
M = molecular weight
ϱ = density of the liquid
R = gas constant $= \dfrac{1544}{M}$
T = absolute temperature
P_0/P = relative pressure

Based on this equation, the sizes of capillaries for various relative vapor pressures are given in Table 2.6.

In the drying process while most of the capillary water will disappear first, there is simultaneous evaporation of both capillary water and molecularly-held water right from the saturation pressure to the lowest vapor pressure at which capillary water can be held (Barkas, 1953). This makes it difficult to determine precisely what percentage of moisture content is held by capillary absorption and that by molecular adsorption. In a work on equilibrium moisture content of shelled corn, however, it was concluded that in the range of 5 to 90 per cent relative humidity the moisture binding mechanism is predominately multimolecular adsorption (Hall and Rodriguez-Arias, 1958). In the case of cellulosic materials it has been stated that capillary absorption occurs at relative humidities exceeding about 90 per cent (Stamm, 1962).

Table 2.6 Size of capillaries that will fill with water under different relative vapor pressures (from Stamm, 1964)

Relative vapor pressure	Capillary radius (microns)
0.9	0.010
0.95	0.020
0.97	0.035
0.98	0.053
0.99	0.106
0.995	0.210
0.999	1.060
0.9999	10.60

Sorption–desorption isotherm

If a hygroscopic material is placed in a given environment the moisture content which the material would approach if left in that environment for an infinite period of time is called the equilibrium moisture content. The equilibrium moisture content of agricultural products can be estimated from the following empirical equation (Henderson, 1952).

$$1 - rh = e^{(-k'M^n)}\ M^n \qquad (2.2)$$

where

rh = equilibrium relative humidity expressed as a decimal
M = equilibrium moisture content, per cent dry basis
k' = factor varying with material and temperature
n = exponent, varying with materials

The plot of equilibrium moisture content of a material versus relative humidity of the environment at a given temperature is referred to as sorption or desorption isotherms, depending whether the material is being wetted or dried. It has been established that in gels and other hygroscopic materials the sorption–desorption isotherms are sigmoidal in shape and show marked hysteresis as illustrated in the case of corn kernel in Fig. 2.13. In these curves, at any given relative humidity the moisture content reached from a dryer state is lower than that reached from a wetter one. In other words, the amount of water held by these materials is not only dependent upon the equilibrium relative vapor pressure, but is also dependent upon the direction from which equilibrium is approached.

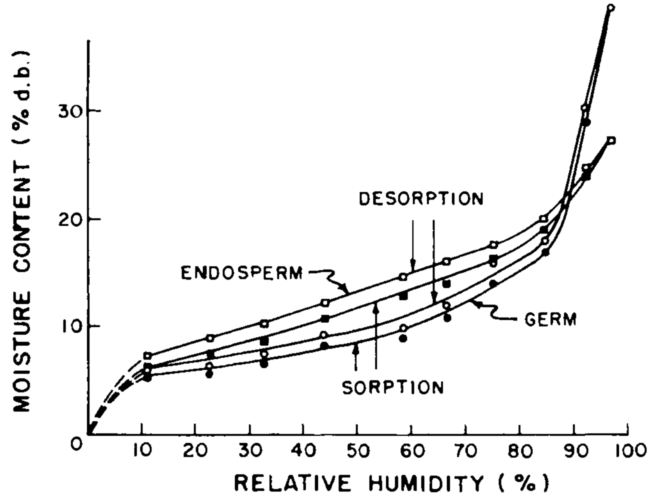


Figure 2.13 Sorption–desportion isotherms for germ and endosperm in corn kernel at 74°F (Shelef and Mohsenin, 1966)

Equation (2.2) above cannot predict a shift in an isotherm due to a change in temperature because the constants k' and n are temperature dependent Also this equation does not predict the hysteresis effect between sorption and desorption isotherms. Several explanations have been proposed for this hysteresis phenomenon. The one favored most is that for the case of cellulosic materials. It is based on the theory of the change in availability of active polar sites for the bonding of water molecules (Stamm, 1964, p. 147). Under this theory, in the original wet condition, the polar sites in the molecular structure of the material are almost entirely satisfied by adsorbed water. Upon drying and shrinkage, the molecules and their water-holding sites are drawn closely enough together to satisfy each other. This reduces the water holding capacity of the material upon subsequent adsorption. In other words, due to the fact that rehydration is never as complete as the original hydration, for any given relative vapor pressure, the material shows a higher moisture content along the desorption curve than it does along the adsorption curve.

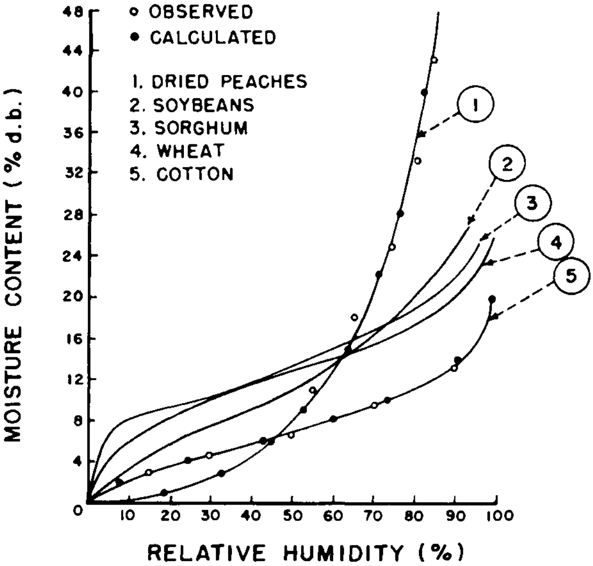


Figure 2.14 Equilibrium moisture curves for several agricultural products (Henderson, 1952)—Similar curves are given by Pichler, 1956; Day and Nelson, 1963; Young and Nelson, 1965

Adsorption equations

Attempts to express the adsorption process mathematically have led to several empirical and derived equations (Freundlich, 1922; Smith, 1947; Brunauer, Emmett and Teller, 1938; Young and Nelson, 1965). The best known and widely used mathematical representation of the adsorption phenomenon in organic materials is, however, given by the so called B. E. T. equation (Brunauer, Emmett, Teller, 1938). A general form of the B. E. T. equation for n molecular layers of adsorbed water is

$$V = \frac{V_m C\,(P/P_0)}{1-(P/P_0)}\,\frac{1-(n+1)\,(P/P_0)^n + n(P/P_0)^{n+1}}{1+(C-1)\,(P/P_0) - C(P/P_0)^{n+1}}$$

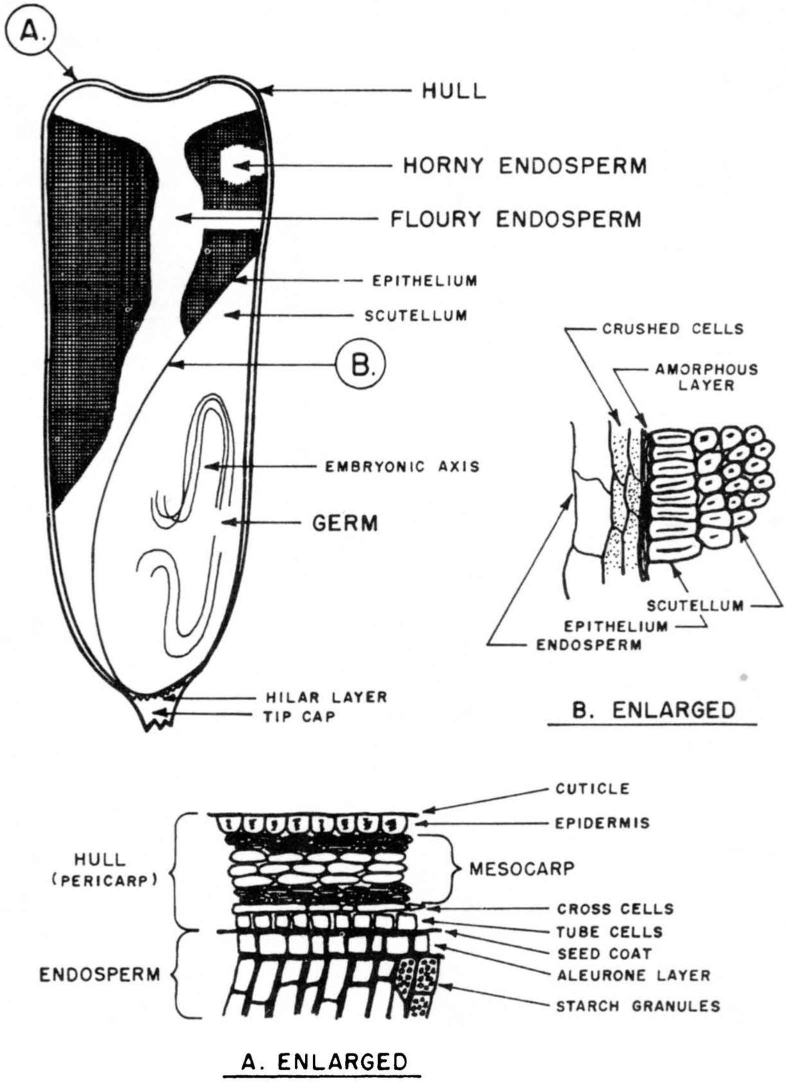


Figure 2.15 Structural elements of the corn kernel (White, 1966)

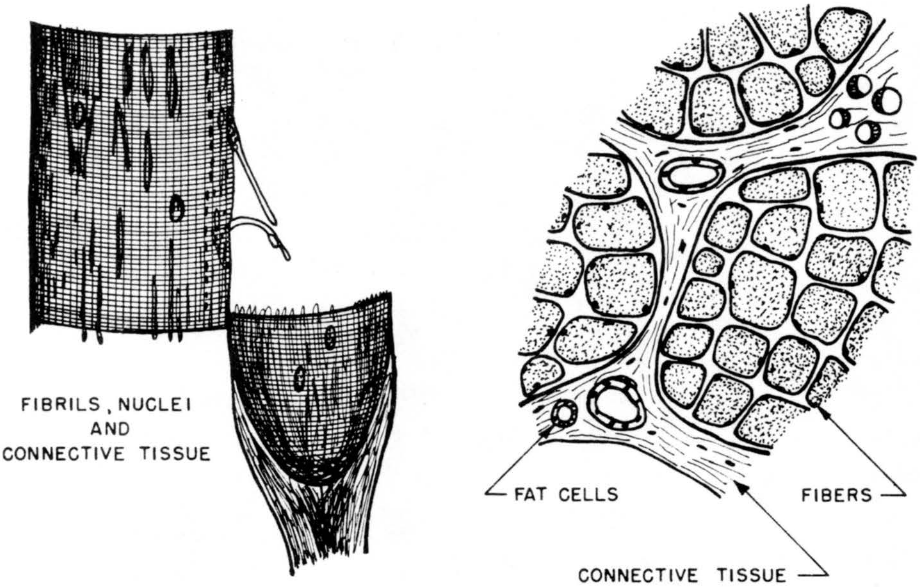


Figure 2.16 Microscopic structure of beef muscle × 160 (A typical fiber is about 50 μ in diameter and many times as long) (Winton and Winton, 1937)

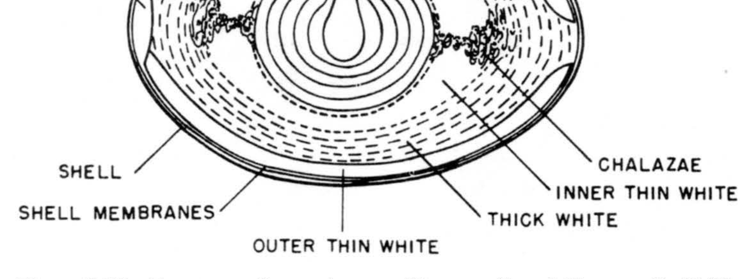


Figure 2.17 Structure of an avian egg (Romanoff and Romanoff, 1949)

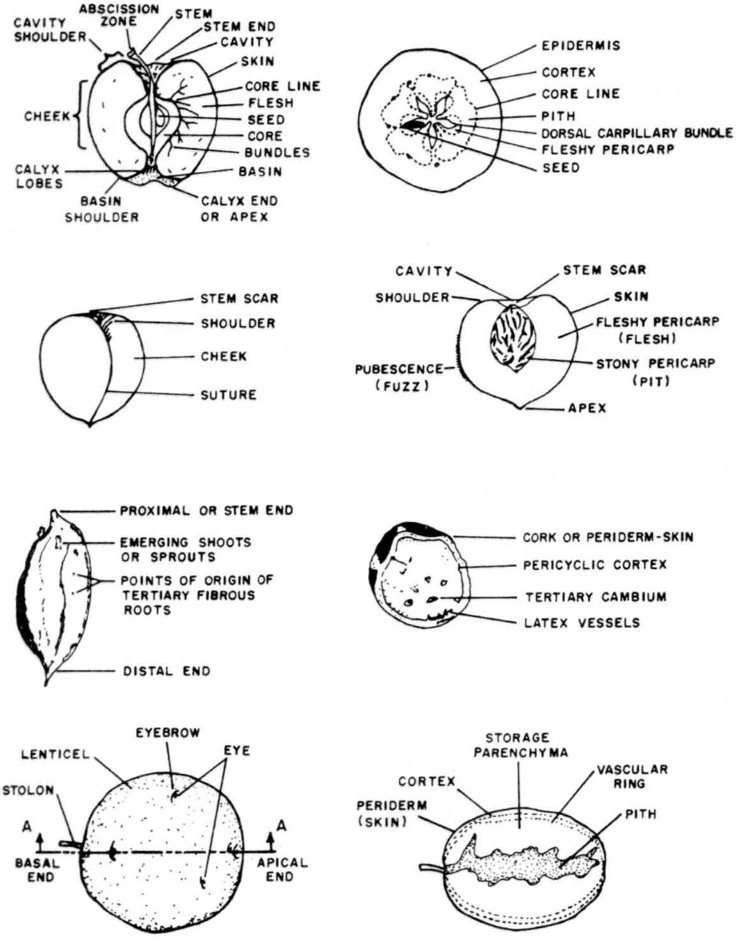


Figure 2.18 Morphological parts of apple, peach, sweet potato, white potato (Mohsenin, ed., 1965).

where

V = volume of gas or vapor adsorbed at vapor pressure, P, per unit weight of adsorbent when the saturation pressure is P_0
V_m = constant representing the volume adsorbed when a monomolecular layer has just been formed
C = constant depending on the heat of adsorption E_a, the heat of condensation E_c, absolute temperature, T, and gas constant, R, such that $C = e^{-(E_a - E_c)/RT}$

If in place of the volume, V, the weight of adsorbate, W, per unit weight of adsorbent is used in the equation, the volume, V_m, will also be replaced by weight, W_m, per unit weight of adsorbent. In the case of sigmoidal types of adsorption curves, the volume, V_m, or weight, W_m, corresponding to the completion of a monomolecular layer, occurs very close to the inflection point in the curve, When $n = 1$, the B. E. T. equation reduces to an expression valid for monomolecular layer adsorption. When $n = \infty$, the equation is valid for multimolecular layer adsorption.

Kunze and Hall (1965, 1967), introduced the method of plotting rice equilibrium moisture content lines directly on a psychometric chart to illustrate grain and ambient environmental conditions relationships in moisture adsorptions and desorption processes.

A review of the literature on the mechanism of adsorption and a discussion of the several adsorption equations are given by Young and Nelson, 1965. These authors have also made an attempt to explain the hysteresis effect in the wetting and drying process of biological materials.

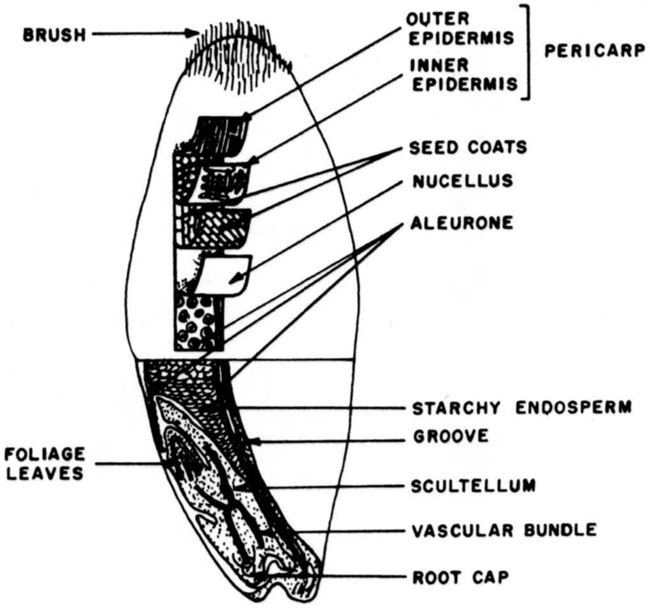


Figure 2.19 Structure of the wheat grain (Robbins, Weier, Stocking, 1957)

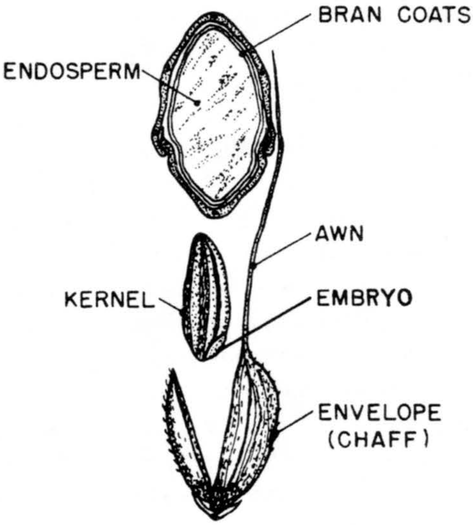


Figure 2.20 Rice: envelope and kernel × 3; cross-section × 12 (Winton and Winton, 1932)

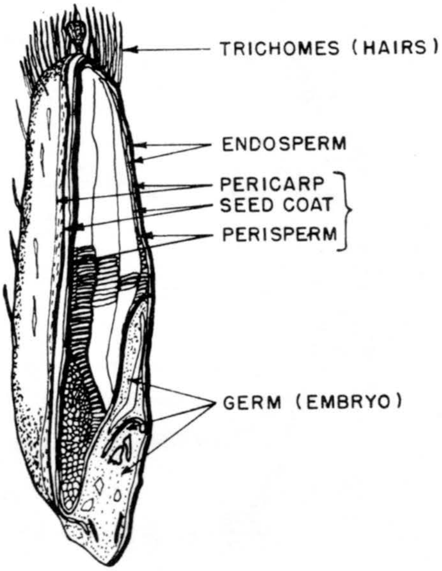


Figure 2.21 Oats kernel with hull removed (Parker *et al.*, 1952)

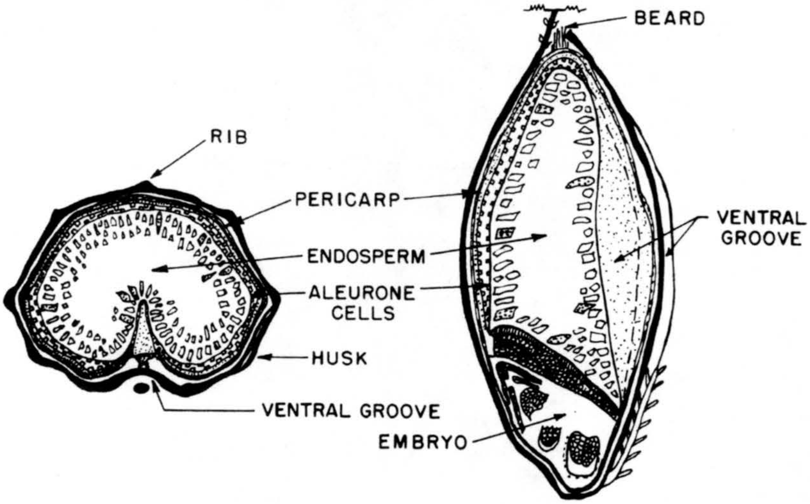


Figure 2.22 Barley kernel (Parker *et al.*, 1952)

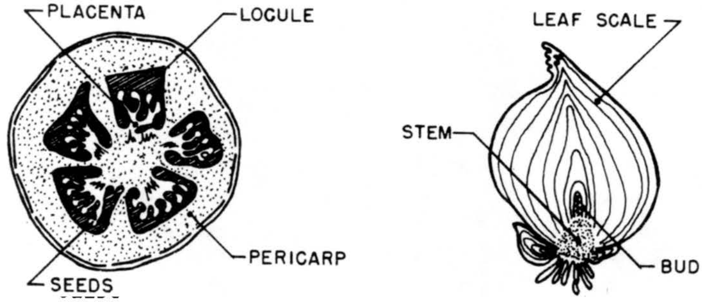


Figure 2.23 Tomato (left), onion (right) (Braungart & Arnett, 1962)

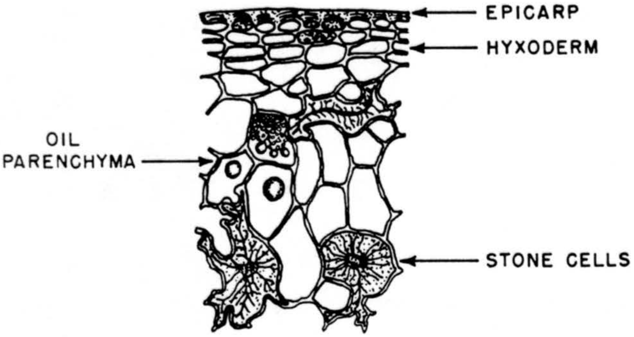


Figure 2.24 Olive: outer pericarp in cross-section × 160 (Winton and Winton, 1932)

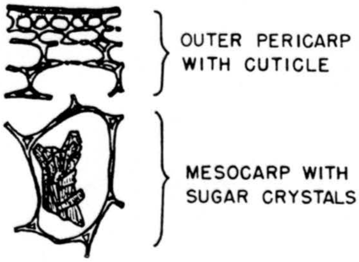


Figure 2.25 American grape × 160 (Winton and Winton, 1935)

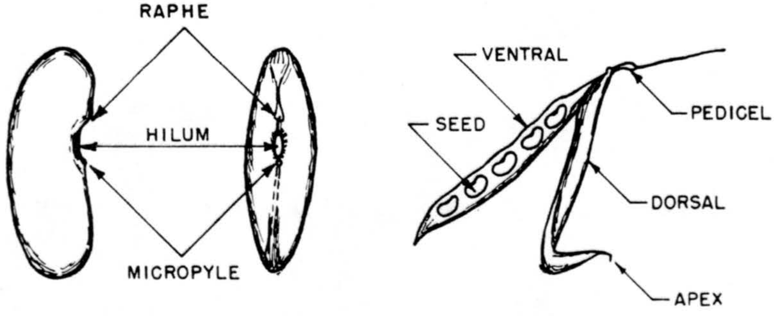


Figure 2.26 Bean seed (Robbins, Weier, Stockings, 1957); bean pod (Mohsenin, ed., 1965)

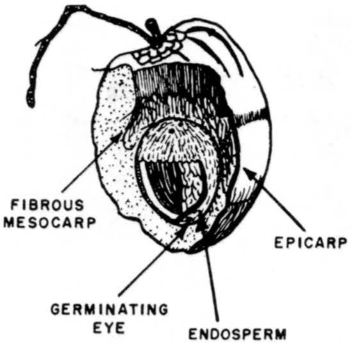


Figure 2.27 Cocoanut fruit × 1/5 (Winton and Winton, 1932)

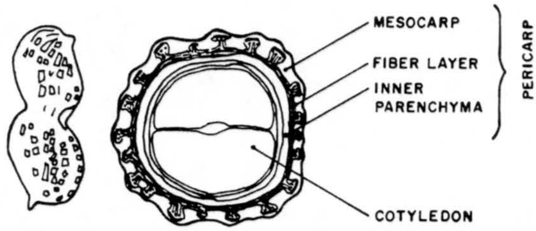


Figure 2.28 Peanut (Winton and Winton, 1932)

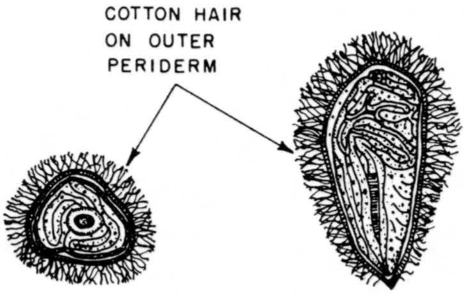


Figure 2.29 Cottonseed: cross-section (left) and longitudinal section (right) (Winton and Winton, 1932)

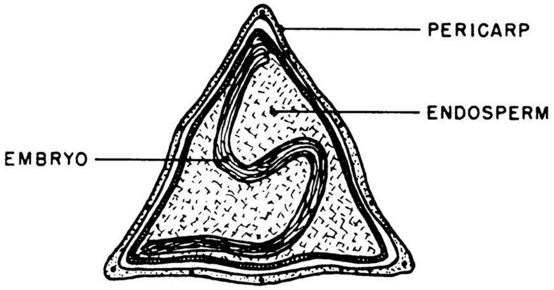


Figure 2.30 Buckwheat × 16 (Winton and Winton, 1932)

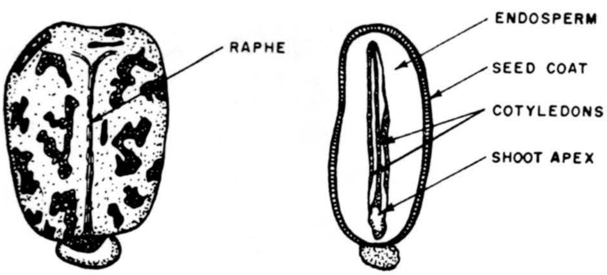


Figure 2.31 Castor bean seed (Robbins, Weier, Stocking, 1957)

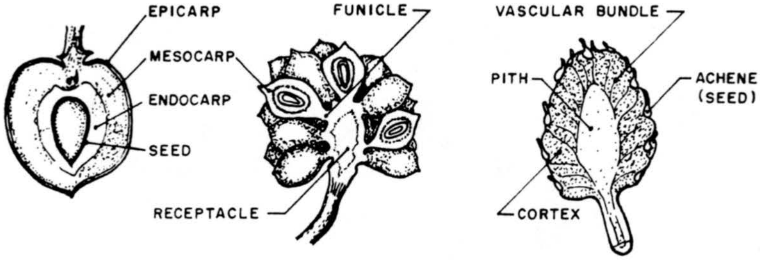


Figure 2.32 Cherry and blackberry (Brook, 1964) strawberry (Braungart and Arnett, 1962)

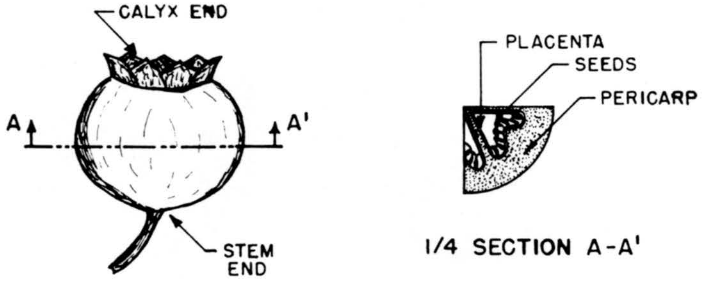
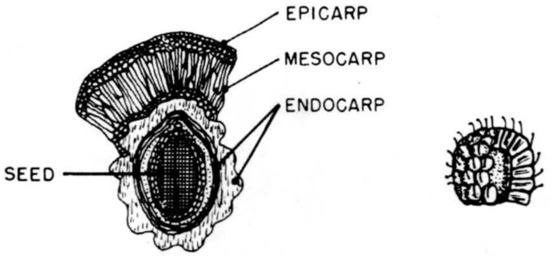


Figure 2.33 Blueberry (Mohsenin, ed., 1965)



DRUPELET IN CROSS SECTION

AGGREGATE FRUIT

Figure 2.34 Raspberry (Winton and Winton, 1932)

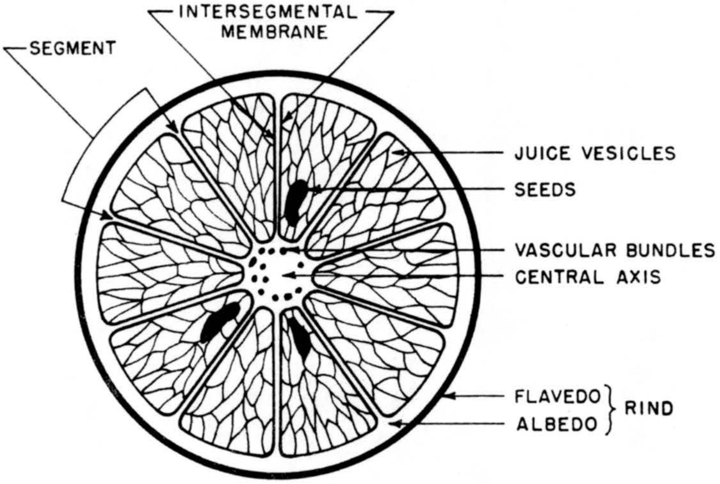


Figure 2.35 Orange (Agriculture Handbook No. 98, 1956 and courtesy James Soule, University of Florida)

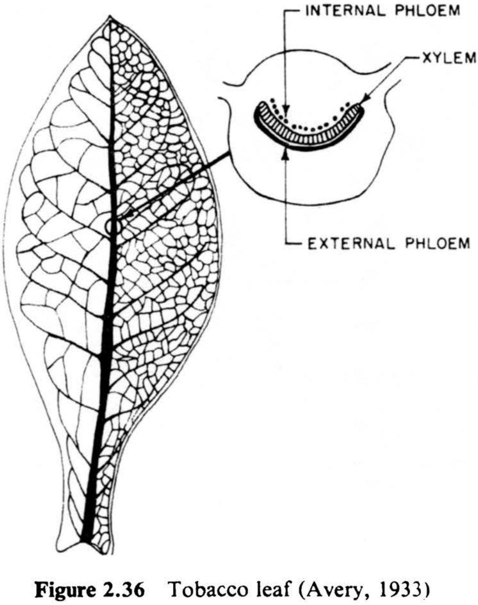


Figure 2.36 Tobacco leaf (Avery, 1933)

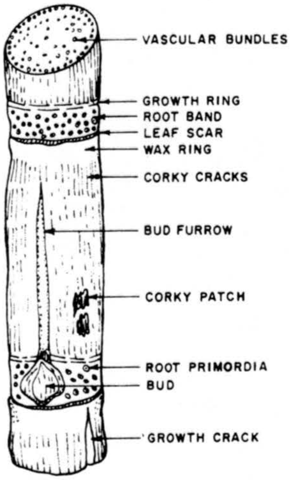


Figure 2.37 Sugar cane (Dillewign, 1952)

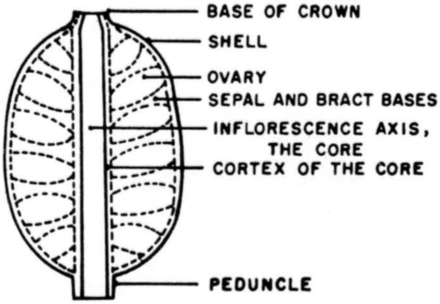


Figure 2.38 Pine apple inflorescence (Okimoto, 1948)

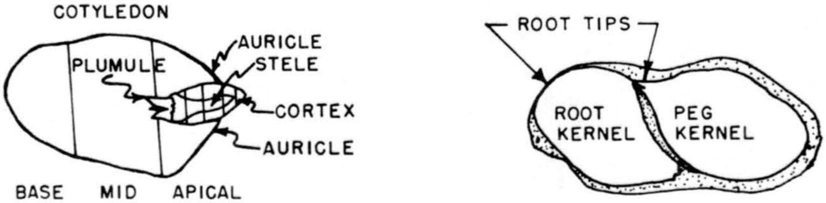


Figure 2.39 Peanut structure. Left: Parts of the embryo. Right: Kernels cradled in the hull (Turner *et al.*, 1965)

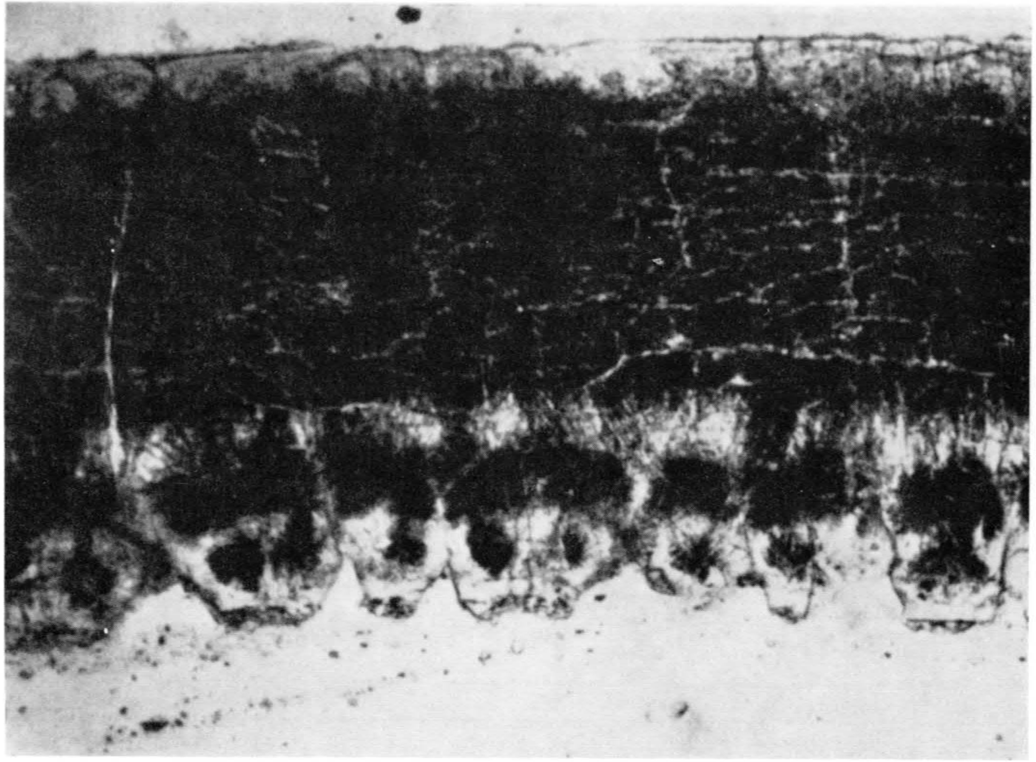


Figure 2.40 Photomicrograph (× 140) of cross section of egg shell 20 μ thick. Egg shell membrane has been stripped away (Terepka, 1963)

Table 2.7 Proximate constituent of some plant products[3]

(Average values in per cent)

Product	Water	Protein	Fat	N-F ext[1]	Fiber	Ash	Starch	Sugar	Solids[2]	Sucrose	Acids
Alfalfa (Hay)	8.36	15.59	1.83	33.38	30.18	10.66					
Alfalfa (green)	71.75	4.84	0.97	12.39	7.39	2.66					
Almond	4.8	21.0	54.9	14.3	3.0	2.0					
Apple	85	0.10				0.27		11.5	16.7	4.00	0.61
Apricot	89.0	0.65				0.51		13.3	12.4	4.3	1.23
Asparagus	93.9	1.83	0.25	2.55	0.74	0.67					
Banana		1.6	0.2		0.50	0.90	3.0	20.2	27.54	8.27	0.41
Barley[3]	9.32	13.39	1.87	76.05	5.64	3.04					
Beets	86.5	1.75	0.10	9.89	0.88	0.88					
Blackberry		0.92				0.59			12.7	0.16	0.91
Black Raspberry		1.02				0.55			14.7	0.10	1.60
Black Walnut	2.5	30.3	57.8	5.8	1.6	2.0					
Blueberry		0.5	3.0	13.0	3.2	0.11			15.0	0.19	0.9
Buckwheat	12.62	10.02	2.24	64.43	8.67	2.02					
Cashew Nut	3.80	9.70	47.15		1.27	2.59	8.90				
Celery	94.5	1.1	0.1	3.3 Total		1.0					
Chick Pea	10.5	22.6	5.0	56.1	3.1	2.9	49.3				
Cocoanut											
(Kernel)	20	6.8	50.6	31.5 Total		1.3					
(Milk)	92.7	0.4	0.15	4.6	0.0	0.80					
Common Bean	89.2	2.3	0.3	7.4	1.9	0.8					
Corn (Cob)	10.68	2.37	0.52	54.89	30.13	1.41					
Corn (Hard)	10.90	10.35	5.00	70.20	1.89	1.49					
Corn (Pop)	10.71	11.22	5.18	69.66	1.76	1.47					

Table 2.7 (continued)

(Average values in per cent)

Product	Water	Protein	Fat	N-F ext[1]	Fiber	Ash	Starch	Sugar	Solids[2]	Sucrose	Acids
Corn (Sweet)	8.82	11.62	8.13	66.72	2.79	1.92					
Cottonseed		30.29	25.76	33.64	14.37	3.24					
Cranberry		0.35	0.51	10.7	1.2	0.17		3.7	12.2		2.3
Cucumber	95.8	0.70	0.09	1.6	0.65	0.42					
Date	15.4	2.1	2.8	78.4		1.3					
English Walnut	2.5	16.6	63.4	16.1	2.6	1.4					
Grapefruit	88	0.6	0.14		1.9	0.5		2.8	11.0	3.1	1.3
Lemon	80	1.04	1.0	15.0	0.08	0.51	0.20	2.0	10.0	0.58	7.8
Lettuce	91.5	1.82	0.6	3.77	1.09	1.22					
Lima Bean	10.4	18.1	1.5	65.9 Total		4.1					
Lime	85	0.78	3.5		0.07	0.66		1.6	9.7	0.00	6.6
Linseed	7.09	24.75	37.28	27.61 Total			3.27				
Maize	12.36	12.11	3.63	68.08	2.39	1.43					
Olive (Pickled)	58.0	1.1	25.9	11.6 Total			1.7				
Onion	85.3	2.3	0.22	10.80	0.76	0.68					
Orange	86.1	1.2	0.4		2.00	0.41		7.1	10.0	4.0	1.6
Peach		0.60				0.65			13.1	7.0	0.6
Pear	82	0.56	0.60	11.5	2.7	0.20			3.1	4.0	0.26
Pineapple		0.50	1.1	13.5	0.20	0.53	5.0		12.5	7.59	1.06
Plum	76.6	1.14				0.77		11.5	12.0	0.11	0.35
Podded Pea	88.6	3.3	0.10	6.10	1.06	0.75					
Red Clover	70.8	4.4	1.1	13.5	8.1	2.1					
Red Clover (Hay)		15.3	3.9	45.8	27.8	7.2					

Table 2.7. (continued)

(Average values in per cent)

Product	Water	Protein	Fat	N-F ext[1]	Fiber	Ash	Starch	Sugar	Solids[2]	Sucrose	Acids
Red Raspberry		1.02				0.55			14.7	0.10	1.60
Rice	12.6	10.3	1.4	73.3	1.0	1.0					
Rice Straw	8.97	4.72	1.87	32.21	32.25	20.00					
Rye	11.59	12.03	1.84	72.64	1.67	1.86					
Shelled Peanut	4.9	29.1	48.8	18.1	2.00	2.3					
Sorghum	12.36	12.11	3.63	68.08	2.39	1.43					
Sour Cherry		1.26				0.6		11.0	20.5	0.46	0.73
Soybean	10.80	33.98	16.85	28.89	4.79	4.69					
Strawberry	86.5	0.80				0.66		5	10.9	0.46	1.21
Sunflower	6.88	15.19	28.29	17.36	28.54	3.20					
Sweet Cherry		1.26				0.6		11.0	20.5	0.46	0.73
Sweet Corn	75.4	3.1	1.1	19.7 Total		0.7					
Timothy (Green)	61.6	3.1	1.2	20.3	11.8	2.1					
Timothy (Hay)		8.0	3.1	52.8	30.7	5.4					
Tomato	93.0	0.85	0.05		0.32	0.60					
Wheat	10.52	11.87	2.09	71.90	1.79	1.83					
Whole Oats	10.00	13.76	4.38	66.29	12.20	3.96					
Winter Squash	88.3	1.4	0.5	9.0	0.8	0.8					

[1] N-F ext nitrogen free extract

[2] Some values are for juice

[3] Winton and Winton, 1935; Jacobs, 1951, 1958

Table 2.7 (continued) Proximate constituents of some animal products

	(Average values in per cent)							
Dairy products: (Jacobs, 1958)	Water	Protein	Fat	Ash	Total solids	Solids not fat	Lactose	Salt
Milk	87.3	3.42	3.67	0.73	12.69	8.77	4.78	—
Butter	13.90	1.18	82.41	—	—	—	—	2.51
Cheese (cheddar)	36.8	23.7	33.8	5.6	—	—	—	—
Meat:								
Beef (Meyer, 1960)	75	22		5.1	1.1			
Pork (Meyer, 1960)	41.9	10.8		44.8	2.1			
Lamb (Winton & Winton, 1937)	58.6	17.8		22.6	1.0			
Chicken (Winton & Winton, 1937)	74.8	21.6		2.5	1.1			
Fish:								
Cod	82.6	16.5		0.4	1.2			
Salmon	64.6	22		12.8	1.4			
White fish	69.8	22.9		6.5	1.6			
Egg (chicken): (Meyer, 1960)								
Whole	73.7	14.8	10.5	1.6				
White	86.2	13.0	0.2	0.6				
Yolk	49.5	16.1	33.3	1.1				

	(Average values in per cent)			
	Organic matter	Calcium carbonate	Magnesium carbonate	Calcium phosphate
Eggshell (chicken) (Winton & Winton, 1937)	4.2	93.7	1.3	0.8

2.8 SELECTED BIBLIOGRAPHY ON STRUCTURE OF PLANT AND ANIMAL PRODUCTS

Bourne, G. H. ed. 1960. *The Structure and Function of Muscle, Vol. I. Structure*. Academic Press, New York.

Bower, F. O. and C. W. Wardlaw. 1947. *Botany of the Living Plant*. Macmillan and Company, London.

Bradbury, O., I. M. Cull and M. M. MacMasters. 1956. Structure of the Mature Corn Kernel. *Cereal Chemistry* 33:329–391.

Briskey, E. J., R. G. Gassens, and J. C. Troutman, ed. 1966. *The Physiology and Biochemistry of Muscle as a Food*. The University of Wisconsin press. Madison.

Esau, K. *Plant Anatomy*. 1953. John Wiley and Sons, Inc., New York.

Esau, K. *Anatomy of Seed Plants*. 1960. John Wiley and Sons, Inc., New York.

Galston, A. W. 1961. *The Life of the Green Plant*. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Giese, A. C. 1957. *Cell Physiology*. W. B. Saunders Company, Philadelphia.

Hayward, H. E. 1938. *The Structure of Economic Plants*. The Macmillan Company, New York.

MacMasters, M. M. 1953. Grain Structure and Grain Storage. USDA, AIC Bull. 348.

MacMasters, M. M. 1962. Important Aspects of Kernel Structure. *Trans. of the ASAE* 5(2):247–249.

Miller, E. C. 1938. *Plant Physiology*. McGraw-Hill Book Company, Inc., New York.

Porter, C. L. 1959. *Taxonomy of Flowering Plants*. W. H. Freeman and Company, San Francisco.

Stiles, W. and W. Leach. 1952. *Respiration in Plants*. Methuen's Monographs on Biological Subjects. John Wiley and Sons, Inc., New York.

Terepka, A. R. 1963. Structure and Classification in Avian Egg Shell. *Experimental Cell Research* 30:171–182.

Tukey, H. B. and J. O. Young. 1939. Histological Study of the Developing Fruit of the Sour Cherry. *Botanical Gazette* 100:723–749.

Tukey, H. B. and J. O. Young. 1942. Gross Morphology and Histology of Development Fruit of the Apple. *Botanical Gazette* 104(1):3–25.

Uphof, J. C. 1959. *The Dictionary of Economic Plants*. Hafner Publishing Company, New York.

Wolf, M. J., C. L. Buzen, M. M. MacMasters and C. T. Rist. 1952. Structure of the Mature Wheet Kernel. Cereal Chemistry 29:321–382.

3

PHYSICAL CHARACTERISTICS

WHEN PHYSICAL PROPERTIES of grains, seeds, fruits and vegetables, eggs, forage, and fibers are studied by considering either bulk or individual units of the material, it is important to have an accurate estimate of shape, size, volume, specific gravity, surface area and other physical characteristics which may be considered as engineering parameters for that product. Table 3.1 is presented to show the application of several of the physical characteristics of potato and stones which have been utilized in design of the separating mechanisms. In this chapter methods for determination of such physical characteristics as shape, size, volume, specific gravity, bulk density and surface area are discussed.

3.1 SHAPE AND SIZE

Shape and size are inseparable in a physical object, and both are generally necessary if the object is to be satisfactorily described. Further, in defining the shape some dimensional parameters of the object must be measured.

In certain applications where both shape and size affect the process, the relationship can be shown by a single, two-dimensional system as follows:

$$I = f(sh, s) \tag{3.1}$$

where I is the index influenced by both shape, sh, and size, s. In other applications the index I may be a function of not only shape and size but also of such other parameters as orientation, o, packing index, p, firmness, f, etc.

$$I = f(sh, s, o, p, f, \ldots) \tag{3.2}$$

A good example is the problem of determining the number of a given fruit required to fill a container. If we substitute Y for I, x_1 for shape, x_2 for size,

Table 3.1 Separation of potatoes and stones, and the properties which are involved[1]

Method of separation	Properties of stones and potatoes								
	Spec. grav.	Depending on spec. grav.			Resilience	Rolling resist.	Air resist.	Shape	Hardness
		Size	Weight	Mass					
Flotation in brine solution	*								
Flotation in sand	*								
Sieve apertures covered by weighted flaps	*	*	*						
Rubber-strip sieve	*	*	*					*	
Single and double coil-spring sieve	*	*	*					*	
Rubber fringed wheel	*	*	*					*	
Rotating brush on "Digger"	*	*		*				*	
Dropping on to rotating brush	*	*	*					*	
Dropping on to rotating wooden drum					*			*	
Dropping on to sloping and vibrating rubber-finger belt	*	*	*		*	*		*	
Placing on to sloping, undulated belt					*			*	
Placing on to a right-angled conveyor belt									
Rolling off wooden drum					*	*		*	
Rolling over sloping surface and wooden drums					*	*		*	
Separation on inclined conveyor belt					*	*		*	
Roller experiments					*	*		*	
Separation on rotating disc						*		*	
Separation by means of a lath						*		*	
Separation of static objects by means of air blast from one side				*		*	*	*	
Dropping through horizontal air stream				*			*	*	
Separation in vertical air stream	*								
Horizontal movement through vertical air stream	*		*			*	*	*	
Separation by means of spikes									*

---

[1] Maak, 1957.

x_3 for orientation, x_4 for packing and x_5 for firmness, we may write the defining equation in multiple regression form as follows:

$$Y = b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 \tag{3.3}$$

This relationship can be evaluated by measuring a set of specimens and the magnitude of the contribution of each x to the variation in y can be estimated by means of analysis of variance and multiple correlation (Quenoville, 1952). This technique has been used in petrography to determine the relationship between such properties as permeability of an oil reservoir and the petrographic properties such as shape, size, mineral composition, arrangement and orientation, etc. of sediments (Griffith, 1958).

Seeds, grains, fruits and vegetables are irregular in shape and a complete specification of their form theoretically requires an infinite number of measurements. From practical point of view, measurement of several mutually perpendicular axes is, however, sufficient. The number of these measurements increases with increase in irregularity of the shape. It is, therefore, important to know what criterion should be used to decide when adequate number of measurements has been made to define the form of the object. In an attempt to establish such a criterion, Griffith (1964) related the volume of a set of specimens of pebbles to their axial dimensions using the following relationship:

$$V = a_1^{b_1}\, a_2^{b_2}\, a_3^{b_3} \ldots a_n^{b_n} \tag{3.4}$$

where V is the volume of the specimen and $a_1, a_2, a_3, \ldots a_n$ are diameters within the body considered as measures of size. Taking logarithm of both sides of the above equation yields the linear expression

$$\log V = b_1 \log a_1 + b_2 \log a_2 + b_3 \log a_3 + \cdots + b_n \log a_n \tag{3.5}$$

Now using multiple linear regression procedure (Goulden, 1952; Quenouille, 1952), volume was related to axial dimensions and the contribution of each axis to volume was determined using the analysis of variance technique (component analysis). It was found that a well-defined linear relationship existed between the log of axial dimensions and log volume of the pebbles. The three mutually perpendicular axes accounted for some 93 per cent of variation in volume. Of this total percentage, the intermediate axis contributed only 4 per cent to volume prediction. In other words, the measurement of only two axes, major and minor axes in this case, conveyed the bulk of the information on variation in log volume. As will be seen later, the third axis may be simultaneously measured, however, with little added inconvenience.

The above technique was used on 50 kernels of dry-shelled corn by measuring the major, minor and intermediate axes as well as weight and specific gravity of each kernel. The volume of the kernel was taken as one of the parameters defining the shape of the kernel and the three mutually perpendicular axes were taken as a measure of size of the kernels. The relationship between shape, size, weight, and specific gravity at different sections of the corn cobs of the same variety as well as a mixture of shelled corn consisting of several varieties are shown in Table 3.2. Note the increasing variance in axial dimensions for samples taken from the middle section of single ears of one variety as compared with those taken from the whole ear of one variety and the whole ears of several varieties. Also, note that correlation coefficients between volume and axial dimensions are higher for the single variety than the mixture of several varieties. From this experiment one may conclude that if estimates of volume are adequate criterion, then measurenemt of three axial dimensions (*a*, *b*, and *c*) should supply the bulk of the information on shape and size of such irregular objects as corn kernels. The methods for measuring these axial dimensions and their use in describing shape and size are discussed in the following sections.

3.2 CRITERIA FOR DESCRIBING SHAPE AND SIZE

Charted standards

In this method tracings of longitudinal and lateral cross sections of the material can be compared with the shapes listed on a charted standard. Figure 3.1 shows examples of charts prepared for apples, peaches, and potatoes. Using standard charts, the shape of the product can be defined either by a number on the chart or by descriptive terms such as the following prepared for fruits and vegetables (Mohsenin, ed., 1965):

Shape *Description*
Round — approaching spheroid
Oblate — flattened at the stem end and apex
Oblong — vertical diameter greater than the horizontal diameter
Conic — tapered toward the apex

Table 3.2 Relationship between three axial dimensions, volume, and specific gravity in 50-kernel samples of shelled corn

Sample and statistics	Major diameter *a* mm	Intermediate diameter *b* mm	Minor diameter *c* mm	Weight W gm	Specific gravity SG	Volume W/density cc	Volume Reg. eq. cc
Single variety middle of ear							
Mean	10.78	7.58	4.57	0.27	1.22	0.222	0.221
Variance	0.475	0.214	0.151	0.001	0.002	0.001	—
Correlation with volume-r	0.66	0.59	0.27	—	—	1.00	—
Regression eq. $\ln V = -7.14 + 1.18 \ln a + 1.04 \ln b + 0.48 \ln c$							
Single variety whole ear							
Mean	11.15	7.30	4.86	0.27	1.24	0.222	0.221
Variance	1.071	0.670	0.586	0.003	0.001	0.002	—
Correlation with volume-r	0.75	0.78	0.30	—	—	1.00	—
Regression eq. $\ln V = -6.19 + 0.62 \ln a + 1.13 \ln b + 0.6 \ln c$							
Mixture of varieties							
Mean	12.66	8.5	5.24	0.35	1.24	0.28	0.29
Variance	1.72	0.77	0.5	0.004	0.004	0.002	—
Correlations with volume-r	0.35	0.41	0.32	—	—	1.00	—
Regression eq. $\ln V = -6.18 + 0.9 \ln a + 0.71 \ln b + 0.68 \ln c$							

Ovate — egg-shaped and broad at the stem end
blique (lopsided) — axis connecting stem and apex slanted
Obovate — inverted ovate
Elliptical — approaching ellipsoid
Truncate — having both ends squared or flattened
Unequal — one-half larger than the other
Ribbed — in cross section, sides are more or less angular
Regular — horizontal section approaches a circle
Irregular — horizontal cross section departs materially from a circle

Visual comparison of the shape of the object with charted standards is a very simple technique but is a psychophysical subjective assessment which suffers from personal prejudice so that different observers achieve different results. It requires elaborate precautions and an experienced observer to ensure reasonable reproductibility. The procedure has been used for estimate of color and various other physical attributes of various materials and shape and size study in geological work and petrography (Curray, 1951).

Roundness

Roundness is a measure of the sharpness of the corners of the solid. Several methods have been proposed for estimating roundness. Those least objectionable are given below (Curray, 1951).

$$\text{Roundness} = \frac{A_p}{A_c} \tag{3.6}$$

where A_p = largest projected area of object in natural rest position
A_c = area of smallest circumscribing circle
The object area is obtained either by projection or tracing (Fig. 3.2).

$$\text{Roundness} = \frac{\sum r}{NR} \tag{3.7}$$

where r = radius of curvature as defined in Fig. 3.2
R = radius of the maximum inscribed circle
N = total number of corners summed in numerator

$$\text{Roundness ratio} = \frac{r}{R} \tag{3.8}$$

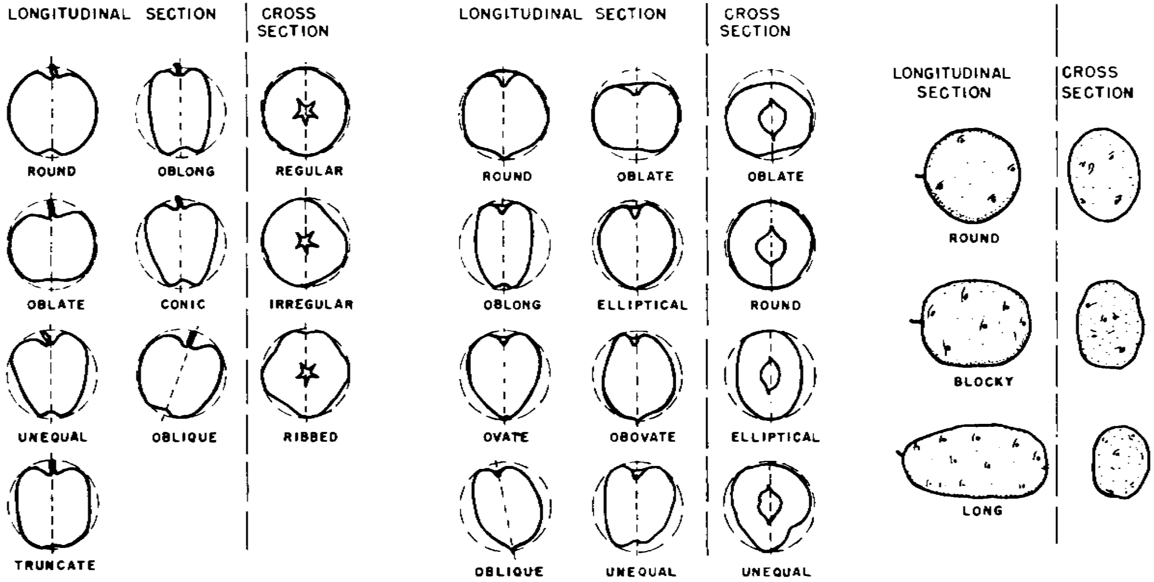


Figure 3.1 Example of charted standard for describing shape of fruits and vegetables. From left to right: apples, peaches, potatoes

where R in this case is the mean radius of the object and r is the radius of curvature of the sharpest corner.

The objection to this method is that the radius of curvature of a single corner determines the roundness or flatness (Fig. 3.2).

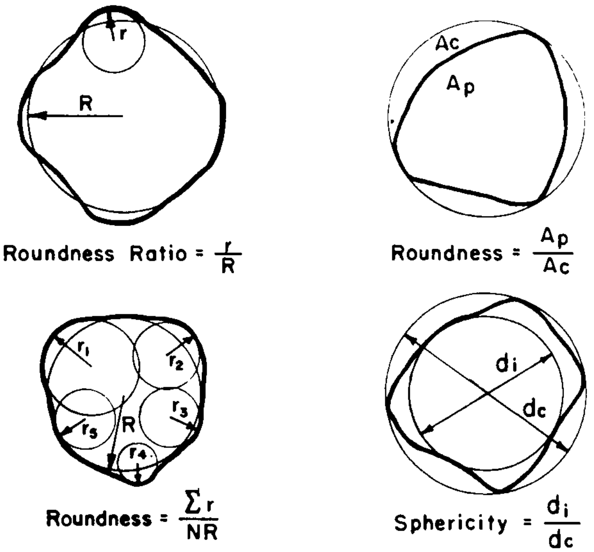


Figure 3.2 Roundness and sphericity as defined by geologists to describe shape of grains and Pebbles (Curray, 1951)

Sphericity

The geometric foundation of the concept of sphericity rests upon the isoperimetric property of a sphere. A practical three-dimensional expression can be stated for estimating the sphericity of an object using the following definition:

$$\text{Sphericity} = \frac{d_e}{d_c} \qquad (3.9)$$

where d_e is the diameter of a sphere of the same volume as the object and d_c is the diameter of the smallest circumscribing sphere or usually the longest diameter of the object (Curray, 1951). This expression for sphericity expresses the shape character of the solid relative to that of a sphere of the same volume.

Assuming that the volume of the solid is equal to the volume of a triaxial ellipsoid with intercepts a, b, c, and that the diameter of the circumscribed sphere is the longest intercept a of the ellipsoid, the degree of sphericity can also be expressed as follows:

$$\text{Sphericity} = \left(\frac{\text{Volume of solid}}{\text{volume of circumscribed sphere}}\right)^{1/3}$$

$$= \left[\frac{(\pi/6)\,abc}{(\pi/6)\,a^3}\right]^{1/3} = \left(\frac{bc}{a^2}\right)^{1/3} \tag{3.10}$$

$$= \frac{\text{geometric mean diameter}}{\text{major diameter}} = \frac{(abc)^{1/3}}{a} \tag{3.11}$$

where a = longest intercept
b = longest intercept normal to a
c = longest intercept normal to a and b

The intercepts need not intersect each other at a common point.

Another definition of sphericity is given by

$$\text{Sphericity} = \frac{d_i}{d_c} \tag{3.12}$$

where d_i = diameter of largest inscribed circle and d_c = diameter of smallest circumscribed circle as shown in Fig. 3.2 (Curray, 1951). Sphericity of several fruits are given in Table 3.3.

Table 3.3 Per cent sphericity of several fruits based on equation (3.10)

Product	Sphericity	Product	Sphericity
Apples		Blueberries	90
McIntosh	90	Cherries	95
Melba	92	Peaches	
Golden Delicious	92	Red Haven	93
Red Delicious	92	Elberta	97
Stayman	90	Pears	
Rome	89	Maxine	89

Measurement of axial dimensions

For small objects such as seeds, the outline of the projection of each sample can be traced using a photographics enlarger. The seed is placed on the plane where the negative is positioned, turned so that its shadow covers the largest