ENGINEERING PROPERTIES OF FOODS

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Summary

The engineering properties of foods are important, if not essential, in the process design and manufacture of food products. They can be classified as thermal (specific heat, thermal conductivity, and diffusivity), optical (color, gloss, and translucency), electrical (conductivity and permittivity), mechanical (structural, geometrical, and strength), and food powder (primary and secondary) properties. Most of these properties indicate changes in the chemical composition and structural organization of foods ranging from the molecular to the macroscopic level. Both modern and more conventional measurement methods allow computation of these properties, which can provide information about the macrostructural effects of processing conditions in fresh and manufactured foods. Mathematical models have been fitted to data as a function of one or several experimental parameters, such as temperature, water content, porosity, or other food characteristics. Most engineering properties are significantly altered by the structural differences between foods. Several microscopy, scanning, and spectrometric technologies permit close visualization of changes in structure at different levels without intrusion. Microstructure studies have increased understanding of several changes detected in foods resulting from treatment in emerging and conventional unit operations, by relating these changes to engineering property characterization data and models. In the future, structure–property modeling could lead to the synthetic production of natural materials with improved characteristics, provided advances in genetic engineering and biotechnology are incorporated into the food engineering field.

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1. Introduction

The word *engine*, derived from the words *engineer* and *engineering*, comes from the Latin word for talent, *ingenium*. From the onset of the Industrial Revolution to the beginning of the twentieth century, the term was used almost exclusively to describe power machines. Those who designed, built, and operated these machines became known as engineers, and their profession, or expertise, as engineering. In today's technological world, the meaning of the term has expanded to include not only such disciplines or activities as chemical, medical, polymer, or food engineering, but also genetic engineering and social engineering. Although these disciplines have little to do with engines, they heavily rely on the ingenuity from which the term was originally conceived.

It is difficult to define what exactly constitutes an engineering property of a certain food. In general, however, any attribute affecting the processing or handling of a food can be defined as an engineering property. Since many properties are related, there is usually an arbitrary element in their classification. Traditionally, they are divided into the following categories:

- *Thermal properties* such as specific heat, conductivity, diffusivity, and boiling point rise, freezing point depression.
- *Optical properties*, primarily color, but also gloss and translucency.
- *Electrical properties*, primarily conductivity and permittivity.
- *Structural and geometrical properties* such as density, particle size, shape, porosity, surface roughness, and cellularity.
- *Mechanical properties* such as textural (including strength, compressibility, and deformability) and rheological properties (such as viscosity).
- Others, including mass transfer related properties (diffusivity, permeability), surface tension, cloud stability, gelling ability, and radiation absorbance.

Nearly all of the above properties are manifestations of a food's chemical composition and structural organization over several orders of length scales—from the molecular to the macroscopic. A change in either composition or structure usually results in a simultaneous change in several properties. Hence it is difficult, if not impossible, to control a single property in isolation. Moreover, properties can be intrinsic, and primarily controlled by the material itself (for example, structural properties like density) and response properties, varying according to the external conditions to which the food is exposed (including colorimetric properties like hue).

Food materials or biological materials in general can display large compositional variations, inhomogeneities, and anisotropic structures. Composition can change due to seasonal variations and/or environmental conditions, or in the case of processed foods, properties can be affected by process conditions and material history. For example, North Atlantic fish show dramatic compositional changes in their protein and moisture contents throughout the seasons. Cereals that are puffed up under different moisture and temperature conditions can vary widely in density and cell-size distribution, and exposure of such products to moist atmospheres, sometimes for short periods only, can have dramatic effects on their crispness. Therefore, in many cases the data found in

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published lists for engineering properties of foods can only be considered as approximate values. Nevertheless, these tabular values are still very useful since a safety factor is added to almost all calculations or designs of food processes and/or operations. An understanding of what affects the engineering properties of foods is essential for their proper interpretation and successful utilization. Therefore, one should always pay attention to the conditions under which the reported properties were determined, especially when response properties are involved.

Early physical property analyses of food products required constant uniform values and were often oversimplified and inaccurate. Nowadays, computational engineering techniques, such as the finite element method, are much more sophisticated and can be used to evaluate non-uniform properties (for example, thermal properties) that change with time, temperature, and location in food products that are heated or cooled. Improvements measuring the compositions of foods are now allowing predictions of engineering properties that are more accurate than previously, since they can be predicted from existing numerical and empirical models of the food's composition, temperature, and porosity. There has always been a tendency to make general correlations in predicting properties of food materials for use in process design equations. A myriad of mathematical functions have already been fitted to experimental data, and models are bringing order to experience with the goal of clarifying which components or interactions are important in a food system.

The *Engineering Properties of Foods* topic covers different sets of engineering properties that are described in greater detail in specific articles, each with wide applications to food engineering and useful for product characterization and equipment design in food manufacture. Basic definitions, common methods, parameter dependence, modeling, and food engineering applications will dictate the basic pattern followed within most sections. The final section will define how engineering properties and microstructure are related, because foods are complex in both structure and composition, this being the main reason for variability during property determination.

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2. Thermal Properties

Most processed and fresh foods receive some type of heating or cooling during handling or manufacturing. Design and operation of processes that involve heat transfer require special attention due to the heat-sensitivity of foods. Thermal properties of foods are related to heat transfer control in specified foods and can be classified as *thermodynamic properties* (enthalpy and entropy) and *heat transport properties* (thermal conductivity and thermal diffusivity). *Thermophysical properties* not only include thermodynamic and heat transport properties, but also other physical properties involved in the transfer of heat, such as freeze and boiling point, mass, density, porosity, and viscosity. These properties play an important role in the design and prediction of heat transfer operations during the handling, processing, canning, storing, and distribution of foods.

Heat can be transferred three different ways: by radiation, conduction, or convection.

- *Radiation* is the transfer of heat by electromagnetic waves (as in a microwave oven).
- *Conduction* is the transfer of thermal energy due to molecular oscillations (for example, heating of food by direct fire through metal containers).
- *Convection* is the transfer of heat by bulk movement of molecules in heated fluids such as liquids or gases (for example, air in heated oven or in tank during juice evaporation).

Although all three types of heat transfer can take place simultaneously, generally only one is predominant, depending on the state of the food and the heating system. In many heat transfer processes associated with storage and processing, heat is conducted through the product; heat is transferred by forced convection between the product and a moving fluid (for example, hot air during tray drying), which surrounds or comes in contact with the product.

Basic definitions of thermal properties of foods related to conduction within the product, with reference to properties associated with forced convection through the surface (such as surface heat transfer coefficient), will be mentioned in this section. Measuring techniques will be briefly described, as well as parameters involved during processing applications.

2.1. Definitions

The thermal properties of foods can characterize heat transfer mechanisms in different unit operations involving heating or cooling. Specific heat, thermal conductivity, thermal diffusivity, boiling point rise, and freezing point elevation are defined as follows:

(a) *Specific heat*, C_p, is the amount of heat needed to raise the temperature of unit mass by unit degree at a given temperature. The SI units for C_p are therefore (kJ kg^{-1} K^{-1}). Specific heat of solids and liquids depends upon temperature but is generally not sensitive to pressure. It is common to use the constant pressure specific heat, C_p, which thermodynamically represents the change in enthalpy H (kJ Kg^{-1}) for a given change in temperature T when it occurs at constant pressure P:

$$C_p = (\delta H / \delta T)_P \tag{1}$$

Only with gasses is it necessary to distinguish between C_p and C_v, the specific heat at a constant volume. Assuming there is no phase change, the amount of heat Q that must be added to a unit mass M (kg of mass or specific weight kg/m^3) to raise the temperature from T_2 to T_1 can be calculated using the following equation:

$$Q = MC_p(T_2\text{-}T_1) \tag{2}$$

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(b) *Thermal conductivity,* κ, represents the quantity of heat $\dot{Q}$ that flows per unit time through a food of unit thickness and unit area having unit temperature difference between faces; SI units for κ are [W m^{-1} K^{-1}]. The rate of heat flow $\dot{Q}$ through a material by conduction can be predicted by Fourier's law of heat conduction. A simplified approximation follows:

$$\dot{Q} = \kappa A(T_1 - T_2)/x \qquad (3)$$

where A is the surface area of the food, x is its thickness, T_1 is the temperature at the outer surface where heat is absorbed, and T_2 is the temperature at the inner surface. In other words, κ represents the ability of the food to transmit heat. Unlike specific heat, κ depends on mass density.

(c) *Thermal diffusivity,*α, SI units [m^2/s], defines the rate at which heat diffuses by conduction through a food composite, and is related to κ and C_p through density ρ [kg/ m^3] as follows:

$$\alpha = \kappa/\rho C_P \qquad (4)$$

Thermal diffusivity determines the speed of heat of three-dimensional propagation or diffusion through the material. It is represented by the rate at which temperature changes in a certain volume of food material, while transient heat is conducted through it in a certain direction in or out of the material (depending if the operation involves heating or cooling). Eq. (4) shows that α is directly proportional to the thermal conductivity at a given density and specific heat. Physically, it relates the ability of the material to conduct heat to its ability to store heat.

In liquid foods, boiling refers to water evaporation, in which water changes from the liquid phase to steam or vapor phase, and water vapor pressure equals the external pressure. Liquid foods contain high molecular weight solids that cause the boiling point to be elevated above that of pure water. The *boiling point rise,* ΔTr, is known as the increase in boiling point over that of water in a given liquid food. As the vapor pressure of most aqueous solutions is lower than that of water at the same temperature, the boiling temperature (boiling point) of the solution is higher than that of pure water.

During freezing, water in the food changes to ice while heat is removed by a refrigeration system. During heat removal, the unfrozen water will still contain dissolved food solids. The presence of dissolved solids will depress the initial freezing point a certain amount ΔT_f below the expected solidification temperature for pure water. *Freezing point depression* is defined as the temperature reduction ΔT_f. Both the boiling point rise and the freezing point depression of a food are related to its solutes concentration.

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2.2. Thermal Variations in Properties and Methods of Determination

Precision and accuracy of measurement are important factors in determining thermal properties variations. In commercial heating or cooling applications, computer techniques nowadays provide accuracies of 2–5 percent for most heat-transfer calculations, which provide much lower relative errors than practical boundary condition determinations (for example, air temperature and velocities).

Several methods are known for measuring specific heat and C_p and thermal conductivity κ experimentally. C_p measurement of foods can be determined by methods of mixtures and differential scanning calorimetry (DSC). For methods of mixtures, a calorimeter of known specific heat is used and C_p is determined from a heat exchange balance. In the DSC method, the sample is put in a special cell where the temperature is increased at a constant heating rate. The specific heat of the food is obtained from a single heat thermogram, which relates heat flow as a function of time or temperature. Two experimental methods to determine κ are the Fitch method and the line source method. In the Fitch method, a solid slab of a certain food receives heat from one layer and conducts it to a copper plug. Conductivity k is obtained from the food's temperature as a function of heat conduction time. The line source method is based on the use of a thermal conductivity probe to measure a temperature–time relation on a thin cylindrical food piece to which constant heat is applied.

Thermal diffusivity α is usually either determined by direct experimental methods or estimated through Eq. (4). Several direct methods for α determination can be based on a one-dimensional heat conduction equation where geometrical boundary conditions are defined. For instance, an apparatus can be used where the sample is located in a special cylinder and immersed in a water bath at constant temperature. Thermocouples located at the center of the sample (axis) and surface of cylinder measure temperature at different heating times. Transient temperature variations are used for the analytical solution. Indirect methods, although they might yield more accurate diffusivity values, require more time and instrumentation for the three-parameter determination (ρ, κ, and C_p).

Boiling point elevation ΔT_r at a certain external pressure can be determined from a thermodynamic equation using the latent heat of vaporization and molar fraction of the food. However, the use of these equations requires knowledge of the proportions of specific components of the foods that cause changes in the boiling points. In many cases, estimates for specific components present in higher concentrations can be used. Sometimes reference liquids under the same vapor pressure conditions can be compared with the food, and charts can be used to determining boiling points at different saturation concentrations. On the other hand, freezing points T_f in foods can be directly determined from the freezing curve (or cryoscope) method without using component concentrations. ΔT_f value can be derived from the temperature plateau after initial temperature depression (or supercooling) on a time-temperature plot. Furthermore, DSC can also be used to determine the onset, peak, and end of freezing.

Foods show extended variability in composition (mainly water, proteins, carbohydrates, fat, ash, and fiber) and structure, and can be turned into even more complex composite

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materials when heated together, as in the case of many canned and packed foods, pastry, confectionery, and a wide variety of prepared foods. Thermophysical properties depend on the chemical composition of the structure, determined by the physical arrangement and phase distribution of a system. Thus, heat transfer by conduction may take place in several forms depending on the tortuosity of the material, which may vary at different locations. As porous materials contain a gaseous phase, the value of the thermal conductivity κ, specific heat C_p, and thermal diffusivity α will depend on the internal and external pore space represented by its porosity (see *Mechanical properties*).

Thermophysical properties are significantly influenced by changes in water content and temperature. During drying, the transfer of heat into food products is accompanied by simultaneous diffusion of water through the product to the surrounding air, provoking differences in thermophysical properties at different regions of the food. Pore size and distribution not only affect heat transfer because of air retention, but also because of the affinity pores have to retain water. The smaller the pore diameter, the greater the surface tension forces, and the more affinity it has for water. Specific heat C_p of foods is drastically influenced by water content. For example, specific heat has been found to vary exponentially with water content in fruit pulps at above ambient temperatures. Furthermore, nonaqueous components show lower C_p. The specific heats of oils and fats are usually about one-half the specific heat of water, while the specific heat of dry materials in grains and powders is approximately one-third to one-fourth that of water. As a result of solute water interactions, the C_p of each individual component in a food differs from the C_p of a pure component, and usually changes with the concentration of soluble solids. The same occurs with thermal conductivity κ, where water shows greater relative magnitudes in comparison to other food constituents. Thus, both κ and C_p increase with increased moisture content. It is common to find a linear relation between thermal conductivity and moisture content at ambient conditions.

The effect of temperature on thermophysical properties is not easy to establish because solids (or semisolids), liquid foods, and food emulsions undergo structural changes. Thermophysical properties of foods change dramatically during the freezing process. Specific heat changes are difficult to predict when free water becomes solid. Bound water or unfrozen water has a different C_p than bulk-frozen water, and ice has a C_p of about one-half that of liquid water. Thus, C_p below freezing is approximately half that of C_p above freezing. Continuous changes in the fraction of frozen water as temperature varies below the freezing point explain this similarity. In fact, specific heat can be utilized to predict the state of water in frozen foods. Thermal conductivity, however, has been found to be high when temperatures allow water to be in liquid or solid state at very low or high temperatures. Yet when temperatures are within the range of -10° to 0 ºC, κ shows its lowest values. Freezing point depression has been modeled with the initial freezing point as a function of water content using linear and quadratic equations.

Some thermophysical property models for food systems have been developed as a function of water content or temperature. Additionally, as composition greatly differs between one food and another, other models are linear combinations of water, fat, protein, carbohydrate and/or ash content, and temperature. C_p has been measured at different temperatures in fresh and dried fruits, meats, cereal grains and cereal products, oils and fats, powders, and other dry foods. Although linear correlations of C_p with

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concentration are known in liquid foods, variations are often neglected for engineering calculations at near room temperature.

General correlations also predict thermal conductivity κ, of food materials for use in process design equations. Linear, quadratic, and multiple correlations of moisture, temperature, and composition can be found for κ in food materials. Some models consider that different components of foods (for example, fibers) are arranged in layers either parallel or perpendicular to the heat flow. In products such as meats, heat is usually transferred parallel to fibers and κ is dependent on the direction of the heat flow. More general in nature are the randomly distributed models, which consider that the food is composed of a continuous phase with a discontinuous phase dispersed within (solid particles being in either regular or irregular array). In porous materials, porosity must be included in the model because air has a κ much lower than that of other food components. Models including density or porosity, and pressure, have been developed in fruits and vegetables, meat and meat products, dairy products, cereals, and starch. Several models for predicting α in foods have also appeared in literature; however, most are product specific and a function of water content or temperature. Although the influence of carbohydrates, proteins, fat, and ash on thermal diffusivity has been also investigated, it was found that temperature and water content are the major factors affecting α. Above freezing temperatures, diffusivity varies linearly with temperature or water composition in some foods, while this is not valid at below-freezing temperatures.

2.3. Food Processing Applications

Food thermal properties play an important role in the quantitative analysis of food processing operations. Numerous food processing unit operations are heat or energy sensitive, and the most well known are shown in Table 1. Heat exchanged and resulting temperature–pressure relations must consider the minimization of reactions such as browning, vitamin loss, and oxidation reduction in order to preserve the acceptability and nutritional value of the food. Thermal properties are useful when evaluating capacities of drying systems, or studying the effect of product shrinkage or internal cracking with the aid of mathematical and numerical drying models. Enthalpy and specific heat are required to calculate the heat load in food processing operations. Specific heat measurement allows evaluation of the structure of foods (for example, fat polymorphism in chocolate).

Operation	**Description**	**Examples**	**Heat transfer medium**	**Processing conditions**
Pasteurization	Removal of pathogenic microorganisms; increasing shelf life	Milk, fruit juices, beer, eggs	Hot water, steam, electricity	63–85 ºC 15 s–30 min

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Sterilization Canning	Sterilization of solids and liquid; 6-month shelf life	Meat, fish, soup, vegetables, fruit, milk, cream, custard, desserts, soup	Hot water, steam	100–125 ºC 15 min–2 h
UHT processing	Sterilization of fluids and aseptic packaging		Hot water, steam direct or indirect	135–150 ºC 1–10 s
Evaporation	Removal of water; production of liquid concentrate	Milk, fruit juices, coffee, cheese whey	Steam	40-100 ºC 2 s–2 h
Dehydration	Removal of water; production of dried material with low water activity	Milk, potato, vegetables, fruit, meat, fish	Hot air, steam, hot water, electricity	150–250 ºC
Cooking and baking	Cooking foods; baking cereal based foods	Catering operations, bread, meat, pipes, cakes	Steam, hot air, microwaves	1 min to several hours
Frying	Immersion in hot oil	French fried potatoes, doughnuts, crisps	Hot oil	100–150 ºC
Chilling	Reducing temperature to just above freezing point	Dairy products, meat, fish, fruit, vegetables, frozen desserts	Cold air, indirect refrigeration (ammonia)	10–0 ºC
Freezing	Reducing temperature to well below freezing point		Cryogenic fluids (liquid nitrogen)	

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Adapted from: Lewis M.J. (1987). *Physical Properties of Foods and Food Processing Systems*. Chichester, UK: Ellis Horwood.

Table 1. Unit operations involving heat transfer in foods

During processing involving heat, temperature within a food changes continuously, varying not only the food C_p but also the κ. When conduction of heat is involved, thermal conductivity is important to predict or control the heat flux and processing times. In a processing system, it is necessary to predict the time end-point of processing to ensure the efficiency of the equipment. It is also desirable to heat and cool foods as rapidly as possible to improve the economics of the process by increasing the capacity and delivering a better quality product. All processing-time prediction models need the thermal conductivity data of food where energy transfer is involved. The speed of heat propagation or diffusion through the material is also related to processing times. Therefore, thermal diffusivity can also participate in processing-time estimation of processes like canning, cooling, freezing, and frying.

The equilibrium freezing point can be used for the prediction of thermophysical properties because of the discontinuity exhibited at that point. Accurate freezing point data can also be used to calculate other colligative properties such as effective molecular weight, water activity, bound, free, and frozen water, and enthalpy below freezing point. Knowledge of freezing point is important for analyzing freezing and thawing times of frozen foods. Freezing point data can be used to ascertain chemical purity with regard to whether a sample differs from a natural or desired condition. The increase in boiling point or boiling point rise (ΔT_r) of liquid foods is a property of interest in evaporators or other types of heat exchanger equipment design and operation.

It is worth mentioning the role of the surface heat transfer coefficient, as it is one of the important parameters necessary to design and control food processing equipment where fluids (air, nitrogen, steam, water, or oil) participate. Although it is not a property of a food, it is used to quantify the transfer rate of heat by convection from a liquid or a gas (especially boiling liquids and condensing vapors) to the surface of the foods. It plays an important role when evaluating the effectiveness of heat transfer in processes where hot water or steam is applied through the evaluation of the overall resistances during heat transfer.

3. Optical Properties

Optical properties are those material properties resulting from physical phenomena occurring when any form of light interacts with the material under consideration. In the case of foods, the main optical property considered by consumers in evaluating quality is color, followed by gloss and translucency or turbidity among other properties. “Color” is the general name applied to all sensations arising from the activity of the retina, and is related to visual appearance of food (shape, size, surface and flesh structure, and defects).

3.1 Definitions

Optical properties are related to consumer judgment on food appearance and produce some kind of visual effect. Among these, color, gloss and translucency can be defined as follows.

- *Gloss* is the name given to light specularly reflected from a plain smooth surface. It can be defined by a goniophotometric curve, which represents the intensity of light reflected at the surface at different angles of incidence and viewing.
- *Color* is essentially a beam of light composed of irregularly distributed energy emitted at different wavelengths. Depending on the type of illumination, the same material can show different light qualities and produce different

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sensations. Foods, along with other materials, have color properties, which depend exclusively on their composition and structure.

- *Translucency* of foods is defined using an opaque-to-transparent scale. In liquid foods, light passing through changes its path randomly (in other words, is scattered) when interacting with suspended particles. Although light can be transmitted or reflected, the human eye only experiences translucency as a sensory attribute distinct from color. Many food products (such as cloudy fruit and vegetable juices) are neither fully opaque nor fully transparent, but are translucent.

3.2. Methods and Applications

The color perceived when the eye views a food is related to the following three factors: the spectral composition of the light source, the chemical and physical characteristics of the food, and the spectral sensitivity properties of the eye. To evaluate the colorimetric properties of a food, two of these factors must be standardized. Although the human eye can give fairly uniform results, it can be replaced by some instrumental sensor or photocell to provide even more consistent determinations. Visual colorimeters facilitate visual comparisons and eliminate differences in interpretation between operators.

In practice, visual measurement of color entails comparing the color problem with reference colors available in printed charts under well-defined and favorable conditions for good, reproducible comparisons. Light source, geometry of viewing, and color of background are the most important factors to control. Description of color for purchase specifications of food commodities or packaging materials involves color tolerances, which are defined in one, two, or three dimensions in color space to avoid variability of the human eye. Several systems of color analysis have been created. The most used are the CIE, Munsell, Hunter, and Lovibond systems.

- In the CIE system, spectral curves indicate how the eyes of normal observers respond to various spectral light types in the visible portion of the spectrum. The system is based on the fact that any color can be matched as a suitable mixture of red, green, and blue. These primary combinations are called *tristimulus* values of color. A certain color can be defined by chromacity coordinates x and y, and by the luminous transmittance or lightness. A chromacity diagram defines different color points that define the standard color of a food. The US Department of Agriculture uses chromacity coordinates to define specifications of color standards for a variety of products.
- In the Munsell system, all colors are described by three attributes: hue (or type of color), lightness (relative to the proportion of light emitted), and saturation or purity (associated with clear to dark perception). The hue scale is based on ten hues distributed on a circumference (scaled 1 to 10); the lightness ranges from black to white (0 to 10) and is distributed on a perpendicular line; the purity is of irregular length beginning with 0 for the central gray to the limit of purity obtainable by available pigments in the Munsell book of color. The Hunter system is also a three-dimensional system using parameters L^*, a^*, and b^* in each dimension: L^* is the lightness (nonlinear), a^* is redness or greenness,

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and b^* is yellowness or blueness. Combination of L^*, a^*, and b^* can be converted to a single color.

- The Lovibond system is a standard method generally used to determine the color of vegetable oils. It involves visual comparisons of light transmitted through a glass couvette using color filters. Vegetable oils are usually expressed in terms of red to yellow. The Lovibond index can also be used to measure color in wines and juices. Computer software packages have been developed that easily convert light transition spectra into CIE, Munsell, Hunter, and Lovibond color indices.

Color can be measured instrumentally with colorimeters, which may be broadly classified as tristimulus colorimeters and spectrophotometers. The difference between spectrophotometers and colorimeters is that the former measures intensity of light through the completely visible spectrum, and colorimeters are designed to measure only some parameters related to sensory colors. Colorimeters are very useful in the quality control of foods, and give results normally correlated with visual measurements. A Munsell colorimeter consists of a circular rotating platform where several colored disks are mixed in different proportions to provide a range of shades to match the color of a certain food product. It is widely used in the food industry for quality control of a number of solid products like tomatoes, fruits, and peanut butter. Tristimulus colorimeters measure both related scales of Munster, Hunter, or CIE systems, which are numerically related. The quality of output for this type of instrument mainly depends on the correct combination of light source, filter, and photocell to obtain a good reproduction of visual response.

Glossmeters measure intensity of light reflected at three angles of incidence and reflection, and normally give results in the form of indices, obtained by comparing the sample reflectance to that of a highly reflective flat glass, used as a calibration standard. These indices are easy to interpret, in contrast to more difficult goniophotometric curves used in the past for classification. Translucency can be the measurement of the reflection of a thin sample against both a white and black background. From these measurements, the value of reflection from an opaque layer is calculated as a ratio between absorption and scattering to measure scattered light. Additional information on the visual appearance of turbid products such as orange juice can be obtained.

Processing can affect food product color through changes in its physical state and/or pigment content. Color measurement techniques can improve the understanding on processing changes and reaction kinetics in foods. Applications of color measurement for food processing research are many and varied. For instance, color measurement techniques are used for recording desirable color changes in canning salmon with higher oil content, defining translucency of the tissues and green pigment degradation after blanching treatment of green peas, studying browning kinetics, or determining the influence of particle sizes in the final color of powders. Characterization of the color of ingredients can also help to predict the color of the final product—for example, control of raw strawberries for processing into jam. In red wine, the percentage of brown component and the relative loss of anthocyanin can be followed by reflectance measurement during storage.

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Glossiness of a product is a property of the smoothness of its surface. When this characteristic is desired, manufacturers try to improve it, as in the case of fruits covered with wax to make them more visually appealing. Translucency is also worth consideration in some liquid foods, such as fruit juices. Its measurement can be determined by considering the contributions of both absorbed and scattered light when traversing these products. For a few clear liquid foods, such as oils and beverages, color is mainly a matter of transmission of light. Other foods are opaque and derive their color mostly from reflection.

Optical properties can be used to perform quality control and continuous inspection during processing operations. Major requirements for a quality control system are ease of calibration and use, stability, precision, speed, cheapness, and industry-wide applicability. A complete color description requires the use of three dimensions, and a control automatic system may be based on this complete specification. Specifications may be set to provide an idea of fruit ripeness, milk or cream discoloration during sterilization, degree of roasting of coffee grains, or browning of apples slices during storage. Continuous color measurements are used in tasks involving color sorting (or "electronic sorting") by using in-line systems. Color sorting is used for a very wide range of food materials in screening defects. Visible, infrared, and ultraviolet laser beams can provide continuous inspection through scanning of product size, symmetry, damage, irregular shape, fill level, and label placement by adding automatic software in connection with mechanical devices. For example, during conveying of pre-fried potato chips, optical devices detect any with defects (for example, black spots), and automatically deploy an air nozzle to deflect their path from the conveyor belt.

4. Electrical Properties

There are two main electrical properties in food engineering: electrical conductivity and electrical permittivity. Electrical properties are important when processing foods involving electric fields, electric current conduction, or heating through electromagnetic waves. These properties are also useful in the detection of processing conditions or the quality of foods.

4.1. Electrical Conductivity and Permittivity

Electrical conductivity is a measure of how well electric current flows through a food of unit cross-sectional area A, unit length L, and resistance R. It is the inverse value of electrical resistivity (measure of resistance to electric flow) and is expressed in SI units S/m in the following relation:

$$\sigma = L/(AR) \tag{5}$$

Electrical permittivity is a dielectric property used to explain interactions of foods with electric fields. It determines the interaction of electromagnetic waves with matter and defines the charge density under an electric field. In solids, liquid, and gases the permittivity depends on two values:

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- the dielectric constant ε’, related to the capacitance of a substance and its ability to store electrical energy; and
- the dielectric loss factor ε”, related to energy losses when the food is subjected to an alternating electrical field (i.e., dielectric relaxation and ionic conduction).

The electrical conductivity of foods has been found to increase with temperature (linearly), and with water and ionic content. Mathematical relationships have been developed to predict the electrical conductivity of food materials: for example, for modeling heating rates through electrical conductivity measurements, or for probability distribution of conductivity through liquid-particle mixtures. Electrical conductivity shows different behaviors during ohmic and conventional heating. At freezing temperatures, electrical conductivity increases with temperature, as ice conducts less well than water. Starch transitions and cell structural changes affect electrical conductivity, and fat content decreases conductivity. As in thermal properties, the porosity of the food plays an important role in the conduction of electrons through the food.

In foods, permittivity can be related to chemical composition, physical structure, frequency, and temperature, with moisture content being the dominant factor. Dielectric properties (ε’, ε”) are primarily determined by their chemical composition (presence of mobile ions and permanent dipole moments associated with water and other molecules) and, to a much lesser extent, by their physical structure. The influence of water and salt (or ash) content largely depends on the manner in which they are bound or restricted in movement by other food components. Free water and dissociated salts have a high dielectric activity, while bound water-associated salts and colloidal solids have low activity. Power dissipation is directly related to the dielectric loss factor ε” and depends on the specific heat of the food, density of the material, and changes in moisture content (for example, because of vaporization). Permittivity also depends on the frequency of the applied alternating electric field. Frequency contributes to the polarization of molecules such as water. In general, dielectric constant increases with temperature, whereas loss factor may either increase or decrease depending on the operating frequency. Both the dielectric constant ε’ and loss factor ε” decrease significantly as more water freezes.

Reasonable comprehensive tabulations of electrical properties data are available for foods in electronic and printed form.

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4.2. Methods and Applications

The conductivity of a material is generally measured by passing a known current at constant voltage through a known volume of the material and by determining resistance. The total conductivity is then calculated simply by taking the inverse of the total resistivity. Basic measurements involve bridge networks (such as the Wheatstone bridge circuit) or a galvanometer. There are other devices that measure electrical conductivity of foods under ohmic or conventional heating conditions, using thermocouples and voltage and current transducers to measure voltage across and current through the samples.

Known methods for measuring dielectric properties are the cavity perturbation, open-ended coaxial probe, and transmission line methods. Since modern microwave network analyzers have become available, the methods of obtaining dielectric properties over with frequency ranges have become more efficient. Computer control of impedance analyzers and network analyzers has facilitated the automatic measurement of dielectric properties over wide frequency ranges, and special calibration methods have also been developed to eliminate errors caused by unknown reflections in the coaxial-line systems. Distribution functions can be used in expressing the temperature dependence of dielectric properties.

Electrical properties are important in processing foods with pulsed electric fields, ohmic heating, induction heating, radio frequency, and microwave heating. Conductivity plays a fundamental role in ohmic heating, in which electricity is transformed to thermal energy when an alternating current (a.c.) flows through food. As it has potential use in fluid pasteurization, it is important to know the effective conductivity or the overall resistance of liquid-particle mixtures. Furthermore, liquid-particle mixtures can be pasteurized using pulsed electric field technology, where products with low electrical conductivity are better and more energy-efficient to process. Electrical conductivity can be used for acidity studies, therefore, and for monitoring processes where acidity increases, as in fermentations. Crystallization processes (for example, in sugar solutions) can also be monitored with conductivity measurements, as conductivity has been found inversely proportional to viscosity, which in turn follows supersaturation closely. Conductivity measurements have also been used to measure moisture contents in materials, particularly grain products.

The electrical field inside the food is determined by the dielectric properties and the geometry of the load, and by the oven configuration. These properties are also useful in detection processing conditions, or the quality of foods. The major uses for dielectric properties are measuring and heating applications. Permittivity and moisture are closely correlated when the water content is high. Properly designed electrical instruments can be used to determined moisture content or water activity. Knowledge of dielectric properties in partially frozen material is critical in determining the rates and uniformity of heating in microwave thawing. As the ice in the material melts, absorption of energy increases tremendously. Thus, the portions of material that thaw first absorb significantly more energy and heat at increasing rates, which can lead to localized boiling temperatures while other areas are still frozen. Salt affects the situation through freezing point depression, leaving more water unfrozen at a given temperature.

Dielectric properties are also important in the selection of proper packaging materials and cooking utensils, and in the design of microwave and radio frequency heating equipment, because they describe how the material interacts with electromagnetic radiation. Studies of heating uniformity and temperature elevation rate involve dielectric properties. Typical features of power density patterns of a load are large internal hot and cold areas, internal focusing effects, and the edge-heating phenomenon. For example, when a raw egg is heated it may explode because the power density near its center is much higher than in other parts, causing violent shattering as the interior becomes superheated. The dielectric properties of materials are very important in evaluating the

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penetration depth of energy (in other words, the distance at which the power drops 37 percent of its value in the material) that can be achieved in a certain food.

5. Mechanical Properties

The mechanical properties mainly result from the structure, physical state, and rheology. They can be subdivided into two groups: structural and geometrical properties, and strength properties. Structural and geometrical properties include mass–volume–area-related properties (density, shrinkage, and porosity), and morphological properties (surface area, roundness, and sphericity). Strength properties are related to solid and semi-solid stress and deformation, and intervene in food texture and rheological characterization. These properties are needed for process design, estimating other properties, characterizing foods, and quality determination.

5.1. Structural and Geometrical Properties

5.1.1. Density

This is defined as mass per unit volume (the SI unit of density is kg/m^3). Indeed, there are different forms of density such as true, material, particle, apparent, and bulk that can be used, depending on its application in process calculations or product characterization. The volume measurement method is what determines the difference between them. True and material densities are calculated by excluding volumes occupied by internal and external pores within the food, while particle, apparent, and bulk densities are determined from less accurate measurement methods that include pore volume. A material’s volume can be measured by buoyant force, liquid, gas or solid displacement, or gas adsorption, or by estimating the material’s geometric dimensions. The buoyant force method for apparent or particle volume determination utilizes sample weight differences in air and water, while the liquid displacement method measures the increase in liquid volume when the material is immersed in a non-wetting fluid such as mercury or toluene. A gas pycnometer is a gas displacement device that uses high-pressure air differences in a sample cell connected to a manometer to determine material volume. Apparent or particle density can be determined by coating particles in order to include internal pores in the volume measured. For solid displacement, sand or glass beads can be used instead.

In most engineering designs, solids and liquids are assumed to be incompressible—in other words, density changes moderately with changes in temperature and pressure. In food engineering, the density of solid and liquid foods changes with temperature and pressure and is dependent on temperature and composition. In the case of liquid foods, no generic equations exist to predict the density. In the literature most of the density data is correlated empirically as a function of temperature, water, solids, and fat content. Different types of nonlinear correlation, such as exponential, quadratic, and cubic, are used to relate density and moisture content.

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5.1.2. Porosity

Porosity indicates the volume fraction of void space or air space inside a material. Volume determination is relative to the amount of internal (or closed) or external (or open) pores present in the food structure. Therefore, like density, different forms of porosity are also used in food processing studies, namely open pore, closed pore, apparent, bulk, and total porosities. Porosity can be measured by direct and microscopic methods, or can be estimated from density data. Porosity in foods is mainly predicted from empirical correlations, which are valid for individual foods under given processing conditions. Fundamental models exist that are based on the conservation of mass and volume, as well as a number of terms that account for interaction of components and formation or collapse of air or void phase during processing.

5.1.3. Shrinkage

This is the reduction in volume or geometric dimensions during processing. When post-processing volume is larger than initial volume, it is termed as expansion. Two types of shrinkage—isotropic and anisotropic—are usually observed in the case of food materials. Isotropic shrinkage is described as the uniform shrinkage of the materials under all geometric dimensions, whereas anisotropic (or non-uniform) shrinkage develops in different geometric dimensions. The former is common in fruits and vegetables while the latter is known in animal tissue, such as in fish. Shrinkage occurs as a result of moisture loss (during drying), ice formation (during freezing), and formation of pores (by drying, puffing, extrusion, and frying). The glass transition theory is one of the concepts proposed to explain the process of shrinkage, collapse, fissuring, and cracking during drying. The methods of freeze-drying and hot-air drying can be compared on the basis of this theory.

Pore disruption and structure hardening, as well as moisture transport mechanisms, counterbalancing internal forces, and environmental pressure, are some of the causes for reduction or collapse in a food structure. Expansion can be caused by gas generation, which is mainly a result of water evaporation and subsequent pore formation within the food structure. More work is needed to develop a fundamental understanding of how pores are formed, or of the collapse mechanism during processing, and their impact on product characterization. Most of the density, shrinkage, and porosity prediction models for liquid and solid foods are empirical in nature. Recent models have been developed to predict porosity during air-drying based on drying temperature, moisture content, initial porosity, and product type.

Two types of *surface areas* are used in process calculations and product characterization—the *outer or boundary surface* of a particle or object, and the *total surface area of a porous object*, or the pore surface area. It is very common to estimate the surface area from its geometric dimensions in the case of a Euclidian geometric object. A Euclidian geometry always has characteristic dimensions and assumes surfaces to be smooth (in other words, with no external pores), such as in spheric, cubic, and ellipsoidal geometries. Many natural patterns are either irregular or fragmented, to such an extreme degree that Euclidian or classical geometry is no help in describing their form. Fractal analysis is used instead to characterize and estimate the surface areas

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of these shapes. Native and physically or chemically transformed food particles can be characterized by fractals to predict the efficiency of the transformation process and food particle properties, such as adsorption capacity, solubility, puffing ability, chemical reactivity, and emulsifying ability to optimize food ingredient selection for product development and process design. Like fractal analysis, neural networks or artificial intelligence may have potential in modeling surface, shape, and other mechanical properties of foods.

Morphological properties such as *roundness* and *sphericity* are also used to characterize a food's shape. Roundness is a measure of the sharpness of the corners of a solid. Sphericity indicates how the shape of an object deviates from a sphere. Sphericity is defined from the volume, surface area, or geometric dimensions of an object. Sphericity and shape factors are also needed in heat and mass transfer calculations.

Size, shape, sphericity, volume, surface area, density, and porosity are important physical characteristics of many food materials in handling and processing operations. Fruits and vegetables are usually graded according to size, shape, and density. Impurities in food materials can be separated by density differences between impurities and foods. Values for surface areas of fruits and vegetables are needed in investigations related to respiration rate in heat transfer calculations for heating or cooling. Density and the shape factor of food materials are also necessary for predicting the freezing and thawing rate. Volume change and porosity are important parameters in estimating diffusion coefficients for shrinking systems. Porosity and tortuousity are used to calculate effective diffusivity during the mass transfer process.

5.2. Rheology and Texture

Mechanical properties are intertwined with rheology when including strength properties. Mohsenin (1986) defines mechanical properties as "those having to do with the behavior of the material under applied forces." Rheology has been defined as "a science devoted to the study of deformation and flow," or as "the study of those materials that govern the relationship between stress and strain." "Stress" is defined as force components acting on a body per unit cross-sectional area or area of the deformed specimen (SI units in Pa). "Strain" is the change in size or shape (SI units in mm or percentage) of a body in response to the applied force (at a certain time or during continuous change as stress is applied). Rheologically, the behavior of a material is expressed in terms of stress, strain, and time effects. Therefore, properties that deal with the motion of the material as a result of an applied force can be included as mechanical forces.

Rheological tests express stress–strain relationships and study strain rate dependency. Ideal solids deform in an elastic Hookean manner, while ideal liquids flow in a viscous Newtonian manner; in each case the behavior is independent of the strain rate. Nonetheless, foods are strain-rate dependent. They usually contain some solid and liquid attributes and, rheologically, are termed viscoelastic bodies. In addition, many possess structural elements that "yield" or rupture when forces are applied, thus changing the stress–strain behavior not only with the applied rate of strain, but also with

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the applied amount of strain. Foods are anisotropic in nature and their mechanical properties may vary in the direction of the stress application.

There are three stresses that are commonly applied to characterize foods mechanically: *compressive* (directed toward the material), *tensile* (directed away from the material), and *shearing* (directed tangentially to the material). Shear stress is the most prevalent with fluids or viscous materials. Since strain is the response of the material to stress, compressive shear and tensile strains can be found. When small deformations are exerted under compression, foods can show a straight line in the stress strain plot, and its slope is called the "Young modulus of elasticity." Rheologically, a material can deform in three ways: elastic, plastic, or viscous; it can be denoted by a spring friction element and a dashpot arranged in series or parallel, respectively, in rheological models.

Different mechanical situations define how stress can act on a food: *static* (constant stress or strain), *dynamic* (varying stress or strain), or *impact* (stress exerted and removed after a very short period of time). Impact during mechanical handling is the most common cause of mechanical damage to foods. Behavior under static or dynamic stresses governs the extent of potential mechanical injury (for example, during hopper storage or discharge) and can provide valuable information on the design of handling machinery. In cases like these, definitions of creep (when constant stress is applied to a body increasing in strain as a function of time) or stress relaxation (when constant strain is applied to a body) play a role. Solid foods are mechanically characterized by compression tests or impact tests. Universal testing machines give curves of normal force versus deformation, shear forces, creep, and stress relaxation measurements.

The most important mechanical-rheological behavior of fluid or viscous foods is the flow behavior, which can be basically defined as Newtonian, pseudoplastic, and Bingham, indicating viscosity of the material and its dependence on shear rate. In processing, flow properties can influence pumping requirements, flow of fluid through pipes, or even extrusion properties. Flow properties can be determined using any variety of available rheometers or viscometers.

The mechanical properties of foods intersect not only with rheological behavior but also with the texture of foods. In fact, mechanical properties form the basis for food's sensory properties related to texture (in other words, properties involved with material resistance to mastication). Furthermore, sensory terms that characterize texture of a food can include the rheological principles of stress, strain, and time effects. Table 2 shows how sensory textural terms are related to typical mechanical characteristics of food. Both the mechanical properties and texture of food relate to the mechanical work that occurs in food processing operations, as they do when they later interact in the consumer's mouth. For instance, during both mastication and industrial size-reduction processes (for example, slicing, grinding, mashing, pressing), it is desirable to weaken the structure so that it will properly disintegrate when forces are applied.

Primary parameters	**Secondary parameters**	**Popular terms**

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Hardness		Soft→Firm→Hard
Cohesiveness	Fracturability Chewiness Gumminess	Crumbly→Crunchy→Brittle Tender→Chewy→Tough Short→Mealy→Pasty→Gummy
Viscosity		Thin→Viscous
Springiness		Plastic→Elastic
Adhesiveness		Sticky→Tacky→Gooey

Adapted from Peleg M. and Bagley E.B., eds. (1983). *Physical Properties of Foods.* Westport, CT: AVI Publishing.

Table 2. Mechanical characteristics of food texture

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In this way, texture can be defined as those physical characteristics arising from the structural elements of the food that are sensed primarily by the feeling of touch, related to deformation, disintegration, and flow of the food under a force, and measured objectively by functions of mass, time, and length. This indicates that texture studies include structure (molecular, microscopic, and macroscopic) and the manner in which structure reacts to applied forces. It also emphasizes that texture is a multidimensional property comprising a number of sensory characteristics. For instance, the Texture Profile Analysis widely used in industry defines mechanical parameters such as hardness, fracturability, cohesiveness, springiness, chewiness, gumminess, and resilience. Compression tests evaluate texture by compressing the food in one direction and unrestraining it in the other two dimensions to evaluate hardness or strength in solid foods. The puncture test is the oldest one used for food texture determination, and involves the measurement of force necessary to penetrate the test material with a punch. Sometimes puncture tests imitate the failure involved in mastication and can measure the firmness of a fresh fruit. The introduction of computer readout and analysis of force-time plots obtained with Universal Testing Machines allow reading of the maximum forces from the force–time graphs, measuring of slopes, and calculation of areas under the curve, among other features. Highly complex analyses of force–time plots have now become routine.

Structure may refer to the often-complex organization and interactions of food components under the influence of external and internal physical forces. Structure also refers to the size and shape of the components of the food, as well as how they interact to form an organization. Thus, texture properties can predict deformation mechanisms after stress application, effects of heating in baked products, thawing or freezing mechanisms in meats, or changes in the hardness of fleshy fruit tissues during ripening, through structural microscopy studies. Surface structure microscopy can complement the characterization of the strength properties through traditional qualitative methods such as scanning electron microscopy or confocal laser scanning, among other microstructural methods.

6. Properties of Food Powders

Food powders are particle systems that can be used as food products or ingredients. Particle characterization—description of primary properties of food powders in a particulate system—underlies all work in particle technology. Primary particle properties such as particle shape, particle density, porosity, and particle size, control secondary or bulk properties such as mechanical compressibility, cohesion, angle of repose, flowability, segregation, and attrition, among others. Various methods assess both primary and bulk properties of food powders for quality control or process characterization. Powder properties contribute to the understanding of operations like grinding, filtration, sedimentation, centrifugation, spray or freeze-drying, conveying, dosing, hopper storage, mixing, and many others where particles are present as an initial or final product.

6.1. Primary Properties

Several single particle characteristics influence a powder's mechanical properties. These include particle size, particle shape, surface roughness, density, hardness, and adsorption properties. Of these features, *particle size* is the most important. The "size" of a powder or particulate material is relative. For a particulate material to be considered powder, its approximate median size (50 percent of the material is smaller than the median size and 50 percent is larger) should be less than 1 mm. It is also common practice to talk about "fine" and "coarse" powders; several attempts have been made to standardize particle nomenclature. SI units for particle size are micrometers (or microns) or millimeters depending on the size range. The selection of a relevant characteristic particle size measurement depends on *particle shape*, which is rarely spherical. Among varied shapes, particles may be compact, plate-like, or needle-like. The term "diameter" refers to the characteristic linear dimension. Particulate food materials are mostly organic in origin and possess diverse individual structures, ranging from extreme degrees of irregularity (ground materials like spices) to an approximate sphericity (starch) or well-defined crystalline shapes (granulated salt). Many definitions have been established to define individual particle diameter.

More important than individual size is the *size distribution* among the particles. Particle size distribution is directly related to material behavior and/or physical properties of products. Bulk density, compressibility, and flowability of a food powder are highly dependent on particle size and its distribution. In quality control or system property description, measurement of the particle size distribution in food powders becomes paramount. Different types of methods such as sieving, microscope counting techniques, sedimentation, and stream scanning are available for measuring particle size distribution.

Particle *density* and *porosity* have been discussed previously, and all of the above-mentioned classifications apply to particulate systems as well. Other definitions to take

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into account are the “loose bulk density” measured after a powder is freely poured into a container, or “compact density” after it is allowed to compress by mechanical pressure, vibration, and impact. In particle technology, density measurement is important in separation processes (in other words, sedimentation and centrifugation) and in pneumatic and hydraulic transport of powders and particulates, or for processing condition definitions. In particular, dehydration or agglomeration processes can significantly affect the extent and nature of pore formation, and hence the true particle density of the material. During mixing, transportation, storing, and packaging particulate material, it is also important to know the primary properties of bulk material.

6.2. Secondary Properties

Bulk density control is a major objective of many food processes, especially when spray drying and grinding. Under low compressive loads (for example, during powder storage on hoppers), bulk density can be related to normal stress. Bulk density and normal stress have been associated in empirical logarithmic or semi-logarithmic relationships, from which a constant slope value is defined as *mechanical compressibility*. A simultaneous decrease in a powder’s loose bulk density and increase in compressibility indicate greater attractive and cohesive interactions among powders. Mechanical compressibility can also be determined from stress–strain data using Universal Testing Machines or compaction tests, which put the bulk sample in a vertically vibrating system. Compaction tests simulate density changes during handling and transportation.

Binding and frictional interactions among particles when forming a static heap can give an idea of flowability among particles when variations in composition or moisture content occur. The angle that a powder heap forms with the horizontal is denominated *angle of repose*. More cohesive powders form higher angles while lower angles represent greater flowability to some degree. If determined under pertinent conditions, this magnitude can provide useful information in the design of conveyors or bin discharge. It is also widely used in the food ingredient industry for bulk quality control.

Flow properties determine how a powder will behave in bins, hoppers, feeders, and other handling equipment. They deal with difficulties associated with withdrawing material from storage hoppers without interruption and at the required rate. *Flowability* is the ease at which a powder flows through a chute or hopper. Flow of powders is approached differently from known rheological evaluations of flow in fluids. In powders, interactions are studied from the shear stresses needed to make the powder flow under specified normal stress conditions. Shear cells are used according to standard procedures such as Jenike’s method. Some powders may not flow because of particle interlocking or friction among particles, which contributes to stabilizing structures in hoppers during storage. Others possess additional inter-particle forces such as electrostatic, van der Waals, or solid-liquid bridging, providing increased compact strength and cohesion among particles and decreasing flowability even more.

Mechanical and chemical interactions among powders depend on the powder’s composition, moisture content, surface mechanical characteristics, particle history (for example, from production to storage), particle shape and size, and the manner in which the particles interact geometrically. Food powder particles can also stick together and

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form stable structures or cakes that can prevent flow due to mechanical forces resulting from variations in temperature and composition (especially moisture and fat content). *Caking* is the unwanted, spontaneous agglomeration process that produces mechanically stable lumps in powders, where both size distribution and strength of the agglomerates can vary dramatically. This phenomenon is commonly found in foods with low molecular weight compounds and increased moisture such as fruit powders, sugars, or coffee, and it may occur in different drying processes during powder production.

Many food powders (for example, instant beverages or dry soup mixes) are mixtures of two or more particles of different composition. During conveying, mixing, discharging, charging, bulk storage, and packaging of powders, another undesirable phenomena termed *segregation* might occur. This is the unwanted separation of fine particles from coarse particles induced by motion during different handling and storage activities, and occurs almost exclusively in free-flowing mixtures. Different indices can give an idea of the level of segregation in a mixture. Another phenomenon that is more product-related is powder *attrition*, involving the breakdown of particles. In food powders, it is more frequent in agglomerates, mainly because of their multi-particulate structure. Food agglomerates possess brittle characteristics that make the product susceptible to vibration, compressive, shear, or even convective forces applied to the particles during processing. During impact, breakage of brittle particles can occur, as in instant coffee or milk agglomerates. In such cases, density changes can be attributed, at least partly, to progressive changes in particle size distribution and not only to their spatial rearrangement. Indices that characterize attrition effect on agglomerates and brittle powders have also been developed.

7. Role of Food Microstructure in Engineering Properties

Most engineering properties of foods, including the above-described thermal, optical, electrical, and mechanical properties, are significantly altered by structural differences between foods and within them. By researching a food's structure, behavior of properties under different processing conditions can be explained, and different structure–property relationships determined. Food microstructure studies help to explain the external manifestation of the arrangement of structural elements beyond the resolution of the naked eye. The food engineer's task in structural characterization is to find the scaling laws that translate microstructural data into macrostructural behavior in relation to engineering properties.

Food processing may be viewed as a controlled effort to preserve, transform, destroy, or create structure. Microscopy and related techniques make it possible to visualize and identify food components or changes in structure closely without interfering in the food sample's structural arrangements. Formation, rearrangement, or stabilization of new food structures achieved through processing can be better understood from a qualitative microscopic perspective. However, quantitative characterization of interacting forces or energies involved in the whole structure formation and stabilization through microstructural analysis is still far from being attained.

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7.1. Structural Characterization of Foods

Food processing can be defined as the controlled incorporation of materials and energy into a food. From a structural point of view, it combines different restructuring operations mixing molecules and assemblies until a product is created. Changes in engineering properties of foods can be better explained by following changes in structure. Moreover, visual perception of microstructural phenomena can verge upon the understanding of mechanical, electrical, optical, or thermal changes induced by processing of food.

Structure is the spatial arrangement of structural elements (water and oil droplets, gas cells, fat crystals, strands, granules, micelles, and interface) and assemblies (fibers, proteins, cell walls, cells, and tissue), and their interaction governs values for porosity and density. The scale of observation is important in setting up the engineering problem or in finding a solution, since food elements are viewed differently at different scales. Relationships between engineering properties and structure reflect the interactions occurring at the molecular, ultrastructural, microstructrural, and macrostructural level during food processing. Table 3 defines some elements that can be scrutinized at these scale levels. Structure–property relationships describe the way in which physicochemical, functional, technological, and even some nutritional properties of foods are related to their structure. In engineering, microstructure can integrate structural information and data generated by other physicochemical methods to derive structure–property relationships in foods. Within this framework some general uses can be mentioned:

- to obtain physical and morphological information on the system under study at a relevant scale;
- to understand how natural food materials are assembled at different size scales and organization levels, and identify alternatives for disassembling them;
- to determine the type of breakdown occurring in a food and define compression mechanisms of different types of foods; and
- to monitor the controlled destruction of structure during food processing (for example, release of valuable components, development of new structural compounds).

Scale level	**Intended observations**	**Examples**
Molecular	Molecules and polymers Interactions between functional groups Spatial configuration	Different sizes and types of molecules enzymatic cleavage, hydrogen bonding, and chemical cross-linking. Functional groups.

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Ultrastructural	Macromolecules Natural assemblies	Changes in conformation, association and breakdown of macromolecules. Formation of natural assemblies through nonspecific interactions.
Microstructural	Colloids Elements of processed foods	Droplets, crystals, segregated phases, air cells, aggregates, fiber, filaments, films.
Macrostructural	Major structures or phases	Assemblage and bonding. Compressive failure in solids. Particle-particle solid bridges, vegetable or meat cellular and tissue layers.

From: Aguilera J.M and Stanley D.W. (1999). *Microstructural Principles of Food Processing and Engineering,* 2nd edition. MD: Aspen Publishing.

Table 3. Scale levels of scrutiny to relate food structure and engineering properties

The molecular and supramolecular architecture constituting food structure is continually and increasingly being unraveled by combining powerful analytical techniques such as microscopy, thermal and mechanical analysis, and advanced spectroscopy. A significant number of analytical and microscopy techniques have become available for explaining microstructural phenomena in medicine, biology, and materials science. Technologies already applied include direct light, confocal laser scanning, fluorescence, transmission and scanning electron, scanning probe, and atomic force microscopy as well as microspectrophotometry, immunolabeling, and x-ray analysis.

Direct microscopic observation of controlled experiments on a stage mounted under the microscope can provide structural information at a resolution about 10^3 times smaller than the human eye can perceive. Advanced computer imaging technologies, fluorescent probe developments, and computer designed optics have all been integrally linked with improved analytical light confocal laser scanning microscopes for high-resolution volumetric imaging, used for optically sectioning a sample without intrusion. Fluorescence microscopy is useful in food science since it can detect substances in low concentrations, and thus allows the visualization of materials not possible by other light microscopy methods.

The prevailing need for food scientists to view a wide spectrum of structural organization resulted in the scanning electron microscope (SEM) method, which combines the best features of the light and transmission electron microscope with a magnification of 500 000 times. A wide range of similar microscopes can provide images of surface topography of a specimen at submicron levels, allowing the

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examination of surfaces of uncoated "wet" specimens at ambient conditions. Commercial equipment is now available that allows "miniaturization" heating and cooling (freezing) of thin samples or solutions at controlled rates and visualization through charged-coupled device (CCD) cameras linked to a TV monitor and VCR. Scanning probe microscopy and related high-resolution techniques can scan specimen surfaces at the molecular level, by scanning with a sharp probe closely over the sample surface and measuring some function of distance between the material and probe. They can provide estimates of distance and determine spatial distribution of specific structures (for example, particular macromolecules or elements). Microspectrophotometry is applied to quantitative cytochemistry for determination of nucleic acids, proteins, enzymes, pigments, and hormones. Immunolabeling techniques, the use of probes (antibodies or lecithins) that bind to specific sites on individual molecules, is now a standard method in most histology laboratories. An X-ray microanalysis approach routinely provides results with a spatial resolution in cubic µm and complements information obtained from the above-mentioned techniques.

The development of food materials science requires understanding of the physical properties or function of biopolymeric microstructures. Several techniques used in mechanical and polymer science may be coupled with microscopy simultaneously to observe a structure and measure rheological behavior, thermal transitions, and mechanical properties. Micromanipulation techniques borrowed from biology may well be adapted to assess the engineering properties of cells of tissues. Computer-mediated image analysis can help quantify many of the features revealed by microscopic examination of foods: sizes and shapes of cellular components, thickness of cell walls or particle networks in gels, pore size, and size distributions in gels, relative proportions of various phases, and other properties.

The food engineer views microstructure as an opportunity to return to the traditional engineering concept of assembling building blocks by combining heat, mass, and momentum transfer. Food engineers now have the tools to identify picogram quantities of almost any chemical species, to probe the motility of food molecules, and to look inside them with minimal intrusion and in real time for evaluation of almost any food property and the different structural levels present. In the future, structure–property relationships may, with the help of biotechnology and genetic engineering, contribute to synthesizing natural materials with improved characteristics.

7.2. Practical Implications

Foods are dynamic systems where structures vary during storage, distribution, and preparation depending on factors such as composition, acidity, internal pressures, interacting phases, and environmental conditions such as relative humidity, external pressure, or temperature. Modeling and optimization of engineering properties in current and future food processes will depend not only on better mathematical algorithms or faster and more powerful computers, but also on a clearer comprehension of the underlying phenomena at appropriate relevant scales. During processing, microstructural changes can occur without changing the main composition of a food; they may go unnoticed by the naked eye but be detected using engineering property techniques.

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Food microstructure, phase transitions, density, and porosity strongly affect the thermal and transport properties of foods. In mass or heat transfer processes, where diffusion is the main mechanism, the architecture and properties of the intervening elements may explain the magnitude of effective diffusivity. However, other effects such as shrinkage may also contribute to a low instant diffusivity. The study of heat and transport phenomena of foods and biological materials can be advanced through structure visualization in combination with physical measurements. Heat and mass transfer should be understood at the tissue, cellular, and subcellular levels, so that mechanisms prevailing during processing (such as dehydration and extraction) are clearly identified and modeled. For example, confocal laser scanning microscopy revealed, with minimal intrusion and three-dimensional resolution, that cells in the crust of a fried potato strip remain largely intact and oil free, while oil forms an egg-box arrangement surrounding these cells. Thus, the architecture of a processed solid food can be assisted by models that define diffusion coefficients and include individual properties of the phases. Furthermore, correlations can be made for specific heat and thermal conductivity. In fact, structural conductivity has been modeled in heterogeneous biphasic materials.

The microstructural arrangement of food chemical components affects heat conduction during drying operations. Microstructure can be utilized to develop moisture distribution profiles in drying studies. Furthermore, other common phenomena such as radial cracking and formation of channels during drying (for example, through spherical starch granules) can be characterized. Microstructural studies provide complementary information for the optimization of freezing rates. Freezing involves simultaneous immobilization of water as ice and temperature reduction. Along with ice crystallization, extensive microstructural changes occur inside organized tissues. The rate of freezing will determine the sensory quality of foods, as small crystals can be formed at a faster rate. For example, small crystal formation has a tremendous impact on the sensory evaluation of ice cream. The density and shape factor of food materials are also necessary for predicting the freezing and thawing rates.

Porosity, pore distribution, and cellularity can also be assessed with microstructural information in mechanical, thermal, and electrical property studies. Quantifications of pore distributions can be accomplished by image processing/image analysis using either an image from a microscope, or in the case of macroporous foods, an image directly captured by a video camera and macrolense. Volume change and porosity are important parameters in estimating diffusion coefficients of shrinking systems. In cellular materials, compression functions depend on the type of cell wall collapse occurring, which can be brittle or plastic (as in gels). Techniques that quantify the ruggedness of products such as fractal analysis are used to estimate the surface areas of these shapes. Fractals, in combination with microstructural studies, can predict the efficiency of the transformation process and food particle properties (such as solubility, puffing ability, emulsifying ability) used to optimize food ingredient selection for product development.

Mechanical properties in food microstructure are explained by understanding the main mechanisms leading to structure formation, which can be studied using the most appropriate microscopy techniques and supported by other experimental data. Surface structure microscopy can enhance the characterization of the strength properties through traditional qualitative methods such as transmission light microscopy, scanning electron

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microscopy, and transmission electron microscopy. Furthermore, the kinetics of structural changes can be inferred from rheological or mechanical responses. Mathematical models should be derived based on available structural data and previous findings, which allow predictions of properties for any changes in structure (for example, that induced by change in formulation).

Through structural microscopy studies, texture properties can predict deformation mechanisms after stress application, effects of heating in baked products, thawing or freezing mechanisms in meats, or changes in the hardness of fleshy fruit tissues during ripening. Controlled destruction of biological materials, such as by pressing or reducing particle size, is needed to release valuable components; microstructural characteristics often dictate the type of breakdown of the material. During roller pressing or milling of fruit pulps or powder cakes, microstructural studies define the rotating directions or speeds of metal rollers in order to obtain the desired product in optimal conditions (for example, faster extraction rates from broken and damaged surface cells). Many foods like meats or vegetables have cellular or fibrous structures that determine mechanical properties. Biochemical microstructural changes in meats (for example, during rigor mortis and cooling) can be monitored by following the stress of a slightly stretched sample. Strain hardening of flesh can also be traced to combined microstructural and molecular changes.

During extrusion, macro- and microstructures are formed by diverse frictional and other mechanisms involving heat release or application. Microscopy, gel permeation, chromatography, and viscosity measurements have demonstrated fragmentation of the starch granule during extrusion as a result of shear at the subcellular level. Distinctive desirable textures controlled by die design and extruder operating conditions can be assured from studies that combine mechanical strength properties and microstructural characterization. Understanding the nonlinear interactions between the levels becomes essential to controlling the texture of food.

In rheology, deviations from ideal Newtonian behavior in complex fluids can be traced back by defining the role of macromolecules or particles and their interactions through structural modeling of flow conditions over time. Viscosity will depend on solid-like networks, shear-induced deformation, and transient superstructures at different shear rates. Microscopic image analysis tools can be adapted to represent different shear and normal stresses to express flow at different points of a fluid. Nondestructive methods such as dynamic oscillatory rheometry or mechanical spectroscopy are particularly suitable for this purpose.

Powder flowability is determined by particle deformability and surface roughness (or friction). Flow properties in powders can also be monitored with microstructural surface characterization techniques. Surface topography is also important in determining friction in sliding conveyors and between particles, or attrition in the breakdown of powders. Attrition mechanisms of food powders have been assessed through the detection of crack propagation paths detected by scanning electron microscopy.

Electrical properties can also be used to evaluate desirable or undesirable characteristics of some foods. Some examples that can be correlated with microstructural modeling are

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measurement of heat damage to artificially dried shelled corn, testing the degree of injury and death suffered by plant tissues, detecting frost hardness in some food materials, or determining egg quality and freshness of fish. Optical properties are also related to microstructure due to the compositional chromatic elements of foods. Their distribution within a food can be monitored through hierarchical studies at different levels on the structure and location of these components.

Advances in genetic engineering and biotechnology will forge a new path where naturally synthetic components and raw food materials with modified properties will be fabricated at the molecular and microstructural level. The application of “nanotechnology” will allow the manufacture and positioning of specific molecules or functional groups within food microstructures.

Glossary

Boiling point:	Temperature at which the pressure exerted by liquid vapor equals the pressure exerted by the surroundings of the liquid.
CIE:	Commission Internationale de l’Éclairage.
CLSM:	Confocal laser scanning microscopy.
Electron microscopy:	A type of microscopy that, by using an electron beam, can attain larger resolution than that produced by a light source.
Engineering:	The application of science and mathematics, in which the properties of matter and the sources of energy in nature are made useful to humans for the design and manufacture of complex products.
Extrusion:	The forcing of a material through a die by rotating a screw inside a barrel in order to obtain different shapes such as ribbons or ropes.
Freezing:	A food preservation process that immobilizes the water in a food at low temperatures (generally below –18 ºC), forming ice within an amorphous matrix.
Freezing point:	The temperature at which the liquid and solid states of a food are in equilibrium at a given pressure (normally atmospheric).
Microscopy:	An investigation technique that produces enlarged images of minute zones in an object.
Microstructure:	Study of the arrangements and interactions of elements in a food responsible for its structure, as observed under a microscope.
Porous food:	Food containing a significant internal void space.
SEM:	Scanning electron microscopy.
Steady state:	A term used to describe the relationship between process variables and time. If the variables change over time, the process is known as steady state; otherwise, the process is called non-steady state or transient.
Structure-property relationships:	Relationships between the internal structure, process, and resulting engineering properties of a material.
Thermocouple:	A device for measuring temperature, consisting of two adjoining wires composed of different metals or alloys, which respond to heat

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	with electric tension.
TEM:	Transmission electron microscopy.
Unit operation:	A process step in which a well-defined transformation occurs, such as changes in temperature, location, size, or composition.

Bibliography

Aguilera J.M and Stanley D.W. (1999). *Microstructural Principles of Food Processing and Engineering*, 2nd Edition. Gaithersburg, MD: Aspen Publishing. [A complete reference dealing with the structure of foods and its relation to qualitative, physical, and processing properties, fully illustrated with photomicrographs.]

Barbosa-Cánovas G.V. and Ibarz A. (2003). *Unit Operations in Food Engineering*. Boca Raton, FL: CRC Press. [This book provides basic information on thermal properties and heat transfer operation in combination with detailed unit operation descriptions.]

Fellows P.J. (2000). *Food Processing Technology: Principles and Practice*. Boca Raton, FL: CRC Press. [A review of the main food manufacturing technologies, covering underlying theory, advantages and disadvantages, equipment and principal applications, and effects on the sensory and nutritional properties of foods.]

Hutchings J.B. (1994). *Food Color and Appearance*. New York: Blackie Academic & Professional. [A complete and detailed description of food color properties, their measurement, and their applications.]

Kress-Rogers E. and Brimelow C.J.B. eds. (2001). *Instrumentation and Sensors for the Food Industry*. Boca Raton, FL: CRC Press. [Includes a set of very practical chapters related to in-line measurement of engineering properties for the control of food-processing operations.]

Lewis M.J. (1987). *Physical Properties of Foods and Food Processing Systems*. Chichester, UK: Ellis Horwood. [An introduction to several engineering properties, with examples applicable to food processing operations and equipment selection in food technology.]

Mohsenin N.N. (1984). *Electromagnetic Radiation Properties of Food and Agricultural Products*. New York: Gordon and Breach Science. [Basic concepts of optical and electric properties and their applications in processed foods.]

Mohsenin N. (1986). Physical Properties of Plant and Animal Materials: Structure, Physical Characteristics, and Mechanical Properties. New York: Gordon and Breach Science. [A sourcebook that describes most engineering properties and mechanical properties in detail.]

Nelson S.O. and Datta A.K. (2001). Dielectric Properties of Food Materials and Electric Interactions. In: *Handbook of Microwave Technology for Food Applications* (ed. A. Datta and R.C. Anantheswaran), pp. 69-114. New York: Marcel Dekker. [Basic definitions of electrical properties of food materials, measurement principles and techniques, and dielectric behavior in foods during microwave applications.]
Peleg M. and Bagley E.B. eds. (1983). *Physical Properties of Foods.* Westport, CT: AVI Publishing. [A classic book on strength, rheological properties, and textural properties of foods. Different foods and components are covered, referencing different food technology applications.]

Rao M.A. (1997). Engineering Properties of Foods. In: *Food Engineering 2000*. (ed. P. Fito, E. Ortega-Rodríguez, and G.V. Barbosa-Cánovas), pp. 39–54. New York: Chapman & Hall. [Major accomplishments on engineering properties of foods, such as rheological, electrical, and thermal properties.]

Rahman S. (1995). *Food Properties Handbook*. Boca Raton, FL: CRC Press. [A very complete source for data on physical, thermal, and thermodynamic properties of foods and their role in food engineering.]

UNESCO – EOLSS SAMPLE CHAPTER

Rao M.A. and Rizvi S.S.H. (1986). *Engineering Properties of Foods*. New York: Marcel Dekker. [Thorough definitions and theoretical backgrounds on important engineering properties and methods are provided, with explanations on their effects on different foods.]

Ryynanen S. (1995). The electromagnetic properties of food materials: a review of the basic principles. *Journal of Food Engineering* **26**, 409–429. [Overviews measurement principles of electrical and dielectric properties.]

Welti-Chanes J., Barbosa-Cánovas G.V., and Aguilera J.M. (2002). *Engineering and Food for the Twenty-First Century*. Boca Raton, FL: CRC Press. [Presents advanced studies on how structure is related to the mechanical and functional properties of foods.]

Biographical Sketches

Gustavo V. Barbosa-Cánovas received his B.S. in Mechanical Engineering at the University of Uruguay and his M.S. and Ph.D. in Food Engineering at the University of Massachusetts, Amherst, MA. He then worked as an Assistant Professor at the University of Puerto Rico from 1985–90, during which he was granted two National Science Foundation (NSF) awards for research productivity. Following this he went to Washington State University (WSU), where he is now Professor of Food Engineering and Director of the Center for Nonthermal Processing of Food (CNPF). Dr. Barbosa-Cánovas chaired the Organizing Committee for the 1997 and 1999 Conference of Food Engineering (CoFE). In addition, he is an Editor of the journal *Food Science and Technology International* published by Sage, the journal *Innovative Food Science and Emerging Technologies* published by Elsevier Science, and the Food Engineering theme in the *Encyclopedia of Life Support Systems* (EOLSS) to be published by UNESCO.

Dr. Barbosa-Cánovas is the Editor-in-Chief of the Food Engineering Book Series published by Kluwer Academic and Plenum Publishers (KAPP) as well as of the Food Preservation Technology Book Series published by CRC Press. He has chaired and organized several technical sessions at the American Institute of Chemical Engineers (AIChE) and Institute of Food Technologists (IFT) annual meetings, edited twelve books on Food Engineering topics, and authored, among others, *Dehydration of Foods* (Chapman & Hall), *Nonthermal Preservation of Foods* (Marcel Dekker), *Food Engineering Laboratory Manual* (Technomic), and *Engineering Properties of Biological Materials* (ASAE). Dr. Barbosa-Cánovas is also a member of the editorial board for four technical journals, including the *Journal of Food Engineering*, *Journal of Food Process Engineering, Journal of Food Science and Technology* (LWT), and the *International Journal of Physical Properties of Foods.* He is International Consultant for the United Nations' Food Agriculture Organization (FAO), Associate Researcher for the United Nations' PEDECIBA (a special program to develop basic sciences), and a consultant for several major food companies in the United States.

Pablo Juliano received a B.S. in Chemistry from the University of Uruguay in 1999. In 2000, he was awarded a scholarship from the Organization of American States to pursue graduate studies at Washington State University toward an M.S. in Food Engineering, where he received his Ph.D. in 2006. He also worked in quality assurance at Nestle (Uruguay) between 1996 and 2000, where he applied his ISO 9000 Quality Specialist Degree. Dr. Juliano specialized in food powder technology and high pressure processing of food.

Micha Peleg is Professor of Food Engineering at the University of Massachusetts, Amherst, MA in the Department of Food Science (since 1990). He first obtained his B.Sc. (Chemical Engineering) at Technion, Israel Institute of Technology in 1963, his M.Sc. (Food Engineering and Biotechnology) at Technion in 1967, and his D.Sc. (Food Engineering and Biotechnology) at Technion in 1971. Dr. Peleg's current research areas are mathematical and computer-aided modeling and analysis of rheological behaviors of solid foods, mechanical testing of food materials, viscosimetry, powders, particle size distributions, and microbial populations dynamics.

Editorial board membership: *Journal of Texture Studies* (since 1982), *Journal of Food Science* (1985–l988, since 1999), *Journal of Food Process Engineering* (1987–1990), *Food Science and Technology International* (since 1996), *Journal of Food Properties* (since 1997), Food Engineering Series, Aspen Publishing (since 1998), and *Journal of Food Protection* (2001–2003). Publication referee (partial list): *Transactions of the American Society of Agricultural Engineers*, *Journal of Texture Studies*, *Journal of*

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Food Science, *Powder Technology*, *Journal of Food Process Engineering*, *Food Technology*, *Journal of Food Processing and Preservation*, *Biotechnology Progress*, *Journal of Rheology*, *Rheologica Acta*, *American Institute of Chemical Engineers Journal*, *Food Science and Technology* (lwt), *Journal of Food Engineering*, *Food Hydrocolloids*, *Critical Reviews Food Science & Nutrition*, *Food Microbiology*, *Food Research International*, *Food Science and Technology International*, and *Journal of Material Science*. Research proposals referee (partial list): National Science Foundation, Sea Grant, United States Department of Agriculture, Research Canada, International Science Foundation, and the national research councils of Argentina, Chile and Israel. He has over 250 technical publications to his credit.

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