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Principles of Food Processing

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1.1 Processing of foods: an introduction

Processing of foods is a segment of manufacturing industry that transforms animal, plant, and marine materials into intermediate or finished value-added food products that are safer to eat. This requires the application of labor, energy, machinery, and scientific knowledge to a step (unit operation) or a series of steps (process) in achieving the desired transformation (Heldman & Hartel, 1998). Value-added ingredients or finished products that satisfy consumer needs and convenience are obtained from the raw materials.

The aims of food processing could be considered four-fold (Fellows, 2009): (1) extending the period during which food remains wholesome (microbial and biochemical), (2) providing (supplementing) nutrients required for health, (3) providing variety and convenience in diet, and (4) adding value.

Food materials' shelf life extension is achieved by preserving the product against biological, chemical, and physical hazards. Bacteria, viruses, and parasites are the three major groups of biological hazards that may pose a risk in processed foods. Biological hazards that may be present in the raw food material include both pathogenic microorganisms with public health implications and spoilage microorganisms with quality and esthetic implications. Mycotoxin, pesticide, fungicide, and allergens are some examples of chemical hazards that may be present in food. Physical hazards may involve the presence of extraneous material (such as stones, dirt, metal, glass, insect fragments, hair). These hazards may accidentally or deliberately (in cases of adulteration) become part of the processed product. Food processing operations ensure targeted removal of these hazards so that consumers enjoy safe, nutritious, wholesome foods. With the possibility of extending shelf life of foods and advances in packaging technology, food processing has been catering to consumer convenience by creating products, for example, ready-to-eat breakfast foods and TV dinners, on-the-go beverages and snacks, pet foods, etc. Food processing, as an industry, has also responded to changes in demographics by bringing out ethnic and specialty foods and foods for elderly people and babies. Nutrition fortification, for example, folic acid supplementation in wheat flour, is another function of processing food.

The scope of food processing is broad; unit operations occurring after harvest of raw materials until they are processed into food products, packaged, and shipped for retailing could be considered part of food processing. Typical processing operations may include raw material handling, ingredient formulation, heating and cooling, cooking, freezing, shaping, and packaging (Heldman & Hartel, 1998). These could broadly be categorized into primary and secondary processing. Primary processing is the processing of food that occurs after harvesting or slaughter to make food ready for consumption or use in other food products. Primary processing ensures that foods are easily transported and are ready to be sold, eaten or processed into other products (e.g. after the primary processing of peeling and slicing, an apple can be eaten fresh or baked into a pie). Secondary processing turns the primary-processed food or ingredient into other food products. It ensures that foods can be used for a number of purposes, do not spoil quickly, are healthy and wholesome to eat, and are available all year (e.g. seasonal foods).

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In the previous example, baking of the pie is a secondary processing step, which utilizes ingredient from primary processing (sliced apple).

The food and beverage manufacturing industry is one of the largest manufacturing sectors in the US. In 2011, these plants accounted for 14.7% of the value of shipments from all US manufacturing plants. Meat processing is the largest single component of food and beverage manufacturing, with 24% of shipments in 2011. Other important components include dairy (13%), beverages (12%), grains and oilseeds (12%), fruits and vegetables (8%), and other food products (11%). Meat processing is also the largest component (17%) of the food sector's total value added, followed by beverage manufacturing (16%) (Anonymous, 2012; USDA Economic Research Service, 2013). California has the largest number of food manufacturing plants (www.ers.usda.gov/topics/food-markets-prices/processing-marketing.aspx), followed by New York and Texas. Demand for processed foods tend to be less susceptible to fluctuating economic conditions than other industries.

Some basic principles associated with processing and preservation of food are summarized in this chapter. In-depth discussion can be found elsewehwere (Earle & Earle, 2012; Fellows, 2009; Gould, 1997; Heldman & Hartel, 1998; Saravacos & Kostaropoulos, 2002; Smith, 2003; Toledo, 2007; Zhang et al., 2011), including various chapters in this book.

1.2 Unit operations in food processing

Most food processes utilize six different unit operations: heat transfer, fluid flow, mass transfer, mixing, size adjustment (reduction or enlargement), and separation. A brief introduction to these principles is given in this chapter; more detailed information about the theory behind the principles and applications can be found in standard food or chemical engineering textbooks, including Singh and Heldman (2009), Welti-Chanes et al. (2005), and McCabe et al. (2001).

During food processing, food material may be combined with a variety of ingredients (sugar, preservatives, acidity) to formulate the product and then subjected to different unit operations either sequentially or simultaneously. Food processors often use process flow charts to visualize the sequence of operations needed to transform raw materials into final processed product. The process flow diagrams often include quality control limits and/or adjustment and description of any hazards. Figure 1.1 shows a sample process flow diagram for making Frankfurter comminuted sausage.

1.2.1 Heat transfer

Heat transfer is one of the fundamental processing principles applied in the food industry and has applications in various unit operations, thermal processing, evaporation (concentration) and drying, freezing and thawing, baking, and cooking. Heating is used to destroy microorganisms to provide a healthy food, prolong shelf life through the destruction of certain enzymes, and promote a product with acceptable taste, odor, and appearance. Heat transfer is governed by heat exchange between a product and its surrounding medium. The extent of heat transfer generally increases with increasing temperature difference between the product and its surrounding.

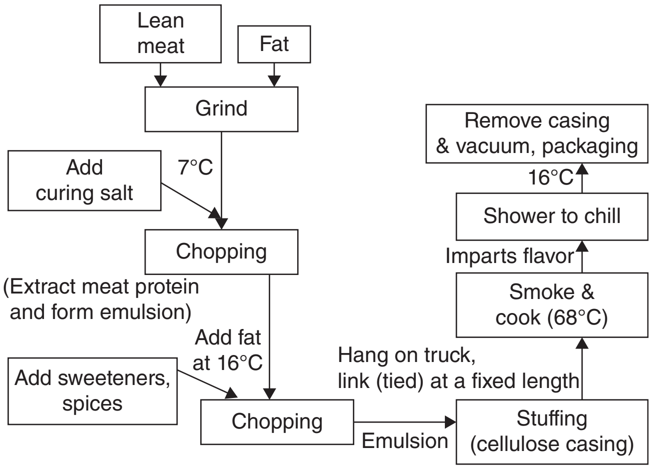

Figure 1.1 Process flow diagram of Frankfurter comminuted sausage manufacturing.

Conduction, convection, and radiation are the three basic modes of heat transfer. Conduction heat transfer occurs within solid foods, wherein a transfer of energy occurs from one molecule to another. Generally, heat energy is exchanged from molecules with greater thermal energy to molecules located in cooler regions. Heat transfer within a potato slice is an example of conduction heat transfer.

Heat is transferred in fluid foods by bulk movement of fluids as a result of a temperature gradient, and this process is referred to as convective heat transfer. Convective heat transfer can be further classified as natural convection and forced convection. Natural convection is a physical phenomenon wherein a thermal gradient due to density difference in a heated product causes bulk fluid movement and heat transfer. Movement of liquids inside canned foods during thermal sterilization is an example of natural convection. If the movement and heat transfer are facilitated by mechanical agitation (such as use of mixers), this is called forced convection.

Radiation heat transfer occurs between two surfaces as a result of the transfer of heat energy by electromagnetic waves. This mode of heat transfer does not require a physical medium and can occur in a vacuum. Baking is one example of heat transfer via radiation from the heat source in the oven to the surface of bread. However, heat propagates via conduction within the body of the bread.

1.2.2 Mass transfer

Mass transfer involves migration of a constituent of fluid or a component of a mixture (Singh & Heldman, 2009) in or out of a food product. Mass transfer is controlled by the diffusion of the component within the mixture. The mass migration occurs due to changes in physical equilibrium of the system caused by concentration or vapor pressure differences. The mass transfer may occur within one phase or may involve transfer from one phase to another. Food process unit operations that utilize mass transfer include distillation, gas absorption, crystallization, membrane processes, evaporation, and drying.

1.2.3 Fluid flow

Fluid flow involves transporting liquid food through pipes during processing. Powders and small-particulate foods are handled by pneumatic conveying, whereas fluids are transported by gravity flow or through the use of pumps. The centrifugal pump and the positive displacement pump are two pumps commonly used for fluid flow (Figure 1.2).

Centrifugal pumps utilize a rotating impeller to create a centrifugal force within the pump cavity, so that the fluid is accelerated until it attains its tangential velocity

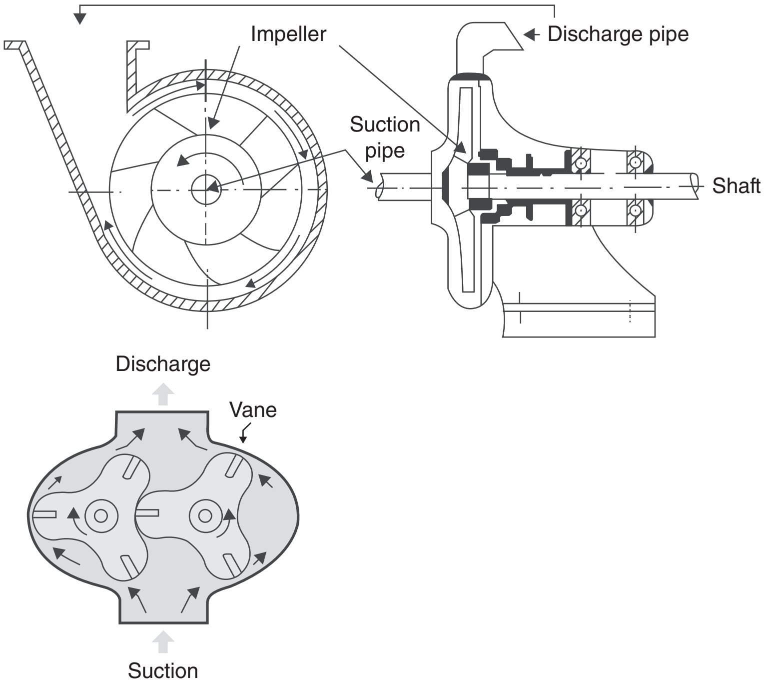

Figure 1.2 Schematic of centrifugal (*top*; from Food and Agriculture Organization of the United Nations 1985 *Irrigation Water Management: Training Manual No. 1 – Introduction to Irrigation*, www.fao.org/docrep/R4082E/R4082E00.htm), and positive displacement pumps (http://en.citizendium.org/wiki/Pump).

close to the impeller tip. The flow is controlled by the choice of impeller diameter and rotary speed of the pump drive. The product viscosity is an important factor affecting centrifugal pump performance; if the product is sufficiently viscous, the pump cavity will not fill with every revolution and the efficiency of the pump will be greatly reduced. Centrifugal pumps are used for transportation of fluids from point A to point B as in transporting fluid for cleaning operations. Centrifugal pumps do not have a constant flow rate.

A positive displacement pump generally consists of a reciprocating or rotating cavity between two lobes or gears and a rotor. Fluid enters by gravity or a difference in pressure and the fluid forms the seals between the rotating parts. The rotating movement of the rotor produces the pressure to cause the fluid to flow. Because there is no frictional loss, positive pumps are used where a constant rate of flow is required (timing pump), for high-viscosity fluids or for transporting fragile solids suspended in a fluid (such as moving cottage cheese curd from a vat to a filler).

1.2.4 *Mixing*

Mixing is a common unit operation used to evenly distribute each ingredient during manufacturing of a food product. Mixing is generally required to achieve uniformity in the raw material or intermediate product before it is taken for final production. Mixing of cookie or bread dough is an example, wherein required ingredients need to be mixed well into a uniform dough before they are portioned into individual cookies or loaves. Application of mechanical force to move ingredients (agitation) generally accomplishes this goal. Efficient heat transfer and/ or uniform ingredient incorporation are two goals of mixing. Different mixer configurations can be used to achieve different purposes (for detailed information, please refer to Fellows, 2009). The efficiency of mixing depends upon the design of impeller, including its diameter, and the speed baffle configurations.

1.2.5 Size adjustment

In size adjustment, the food is reduced mostly into smaller pieces during processing, as the raw material may not be at a desired size. This may involve slicing, dicing, cutting, grinding, etc. However, increasing a product size is also possible. For example, aggregation, agglomeration (instant coffee), and gelation are examples of size adjustment that result in increase in size. In the case of liquid foods, size reduction is often achieved by homogenization. During milk processing, fats are broken into emulsions via homogenization for further separation.

1.2.6 Separation

This aspect of food processing involves separation and recovery of targeted food components from a complex mixture of compounds. This may involve separating a solid from a solid (e.g. peeling of potatoes or shelling of nuts), separating a solid from a liquid (e.g. filtration, extraction) or separating liquid from liquid (e.g. evaporation, distillation) (Fellows, 2009). Industrial examples of separation include crystallization and distillation, sieving, and osmotic concentration. Separation is often used as an intermediate processing step, and is not intended to preserve the food.

1.3 Thermophysical properties, microbial aspects, and other considerations in food processing

1.3.1 Raw material handling

Raw material handling is the very first step in the food processing. Raw material handling includes postharvest transportation (farm to plant), sorting, cleaning or sanitizing before loading into equipment in the plant. These could also be considered as part of primary processing of the food materials. Microorganisms could attach to inert non-porous surfaces in raw foods and it has been demonstrated that these cells transfer from one surface to another to another when contact occurs (Zottola & Sasahara, 1994). Appropriate raw material selection and handling affect microbial safety and final product quality. Future food preservation studies need to consider the impact of raw material (including postharvest handling prior to preservation) on the final processed product.

1.3.2 Cleaning and sanitation

Cleaning and sanitation of raw food material could be considered the first step in controlling any contamination of foreign materials or microorganisms during food processing. Cleaning removes foreign materials (i.e. soil, dirt, animal contaminants) and prevents the accumulation of biological residues that may support the growth of harmful microbes, leading to disease and/or the production of toxins. Sanitization is the use of any chemical or other effective method to reduce the initial bacterial load on the surface of raw materials or food processing equipment. Efficient sanitization includes both the outside and the inside of the plant such as specific floor plan, approved materials used in construction, adequate light, air ventilation, direction of air flow, separation of processing areas for raw and finished products, sufficient space for operation and movement, approved plumbing, water supply, sewage disposal system, waste treatment facilities, drainage, soil conditions, and the surrounding environment (Ray, 2004).

1.3.3 Engineering properties of food, biological, and packaging material

Knowledge of various engineering (physical, thermal, and thermodynamic) properties of food, biological, and packaging material is critical for successful product development, quality control, and optimization of food processing operations. For example, data on density of food material are important for separation, size reduction or mixing processes (Fellows, 2009). Knowledge of thermal properties of food (thermal conductivity, specific heat, thermal diffusivity) is useful in identifying the extent of process uniformity during thermal processes such as pasteurization and sterilization. For liquid foods, knowledge of rheological characteristics, including viscosity, helps in the design of pumping systems for different continuous flow operations. Different food process operations (heating, cooling, concentration) can alter product viscosity during processing, and this needs to be considered during design. Phase and glass transition characteristics of food materials govern many food processing operations such as freezing, dehydration, evaporation, and distillation. For example, the density of water decreases when the food material is frozen and as a result increases product volume. This should be considered when designing freezing operations. Thus, food scientists and process engineers need to adequately characterize or gather information about relevant thermophysical properties of food materials being processed. In-depth discussion of different engineering properties of food materials is available elsewhere (Rao et al., 2010).

1.3.4 Microbiological considerations

Most raw food materials naturally contain microorganisms, which bring both desirable and undesirable effects to processed food. For example, many fermented foods (e.g. ripened cheeses, pickles, sauerkraut, and fermented sausages) have considerably extended shelf life, developed aroma, and flavor characteristics over those of the raw materials arising from microorganisms such as *Lactobacillus*, *Lactococcus*, and *Staphylococcus* bacteria (Jay et al., 2005). On the other hand, raw food material also contains pathogens and spoilage organisms. Different foods harbor different pathogens and spoilage organisms. For example, raw apple juice or cider may be contaminated with *Escherichia coli* O157:H7. *Listeria monocytogenes* are pathogens of concern in milk and ready-to-eat meat. The target pathogen of concern in shelf-stable low-acid foods (such as soups) is *Clostridium botulinum* spores. Different pathogenic and spoilage microorganisms offer varied degrees of resistance to thermal treatment (Table 1.1). Accordingly, the design of an adequate process to produce safer products depends in part on the resistance of such microorganisms to lethal agents, food material, and desired shelf life (see section 4 for details).

1.3.5 Role of acidity and water activity in food safety and quality

Intrinsic food properties (e.g. water activity, acidity, redox potential) can play a role in determining the extent of food processing operations needed to ensure food safety and minimize quality abuse.

Higher acidity levels (pH <4.6) are often detrimental to the survival of microorganisms, so milder treatments are sufficient to preserve an acidic food. Low-acid foods (pH ≥4.6) support the growth and toxin production of various pathogenic microorganisms, including *Clostridium botulinum*. Products such as milk, meat, vegetables, and soups are examples of low-acid foods and require more severe heat treatment than acid foods such as orange juice or tomato products. pH of the food material also impacts many food quality attributes such as color, texture, and flavor. For example, pH of the milk used for cheese manufacturing can help determine cheese texture (hard/soft). Similarly, pH of fruit jelly can determine gel consistency.

Knowledge of availability of water for microbial, enzymatic or chemical activity helps predict the stability and shelf life of processed foods. This is often reported as water activity (a_w), and is defined as the ratio between partial pressure of water vapor (p_w) of the food and the vapor pressure of saturated water (p_w') at the same temperature. The water activity concept is often used in food processing to predict growth of bacteria, yeast, and molds. Bacteria grow mostly between a_w values of 0.9 and 1, most enzymes and fungi have a lower a_w limit of 0.8, and for

Table 1.1 Decimal reduction time (D value, min) of selected pathogenic and spoilage microorganisms found in food material

Pathogenic or spoilage microorganisms	D-value, min*	Temperature, °C	Food
Bacterial spores			
Bacillus stearothermilophilus	2.1–3.4	121	Phosphate buffer (pH 7.0)
Clostridium botulinum (types A and B)	0.1–0.2	121	
Clostridium butyricum	1.1	90	
Clostridium nigrificans	2–3	121	
Bacillus cereus	1.8–19.1	95	Milk
Bacillus coagulans spores	3.5	70–95	
Clostridium sporogenes	0.1–0.15	121	
Clostridium thermosaccharolyticum	3–4	121	
Clostridium perfringens	6.6	100.4	Beef gravy (pH 7)
Molds			
Byssochlamys nivea ascopores	193	80–90	
Neosartorya fischeri ascopores	15.1	85–93	
Talaromyces flavus ascopores	54	70–95	
Vegetative bacteria			
Campylobacter jejuni	0.74–1	55	Skim milk
Escherichia coli O157:H7	4.5–6.4	57.2	Ground beef
Listeria monocytogenes	6.27–8.32	60	Beef homogenate
Salmonella typhimurium	396	71	Milk chocolate
Vibrio parahaemolyticus	0.02–0.29	55	Clam homogenate

*D-value is the time taken to reduce the microbial population by one log-cycle (by 90%) at a given temperature. Adapted from Fellows (2009), Heldman (2003) and Heldman and Hartel (1999).

most yeasts 0.6 is the lower limit. Thus, food can be made safe by lowering the water activity to a point that will not allow the growth of dangerous pathogens (Table 1.2). Foods are generally considered safer against microbial growth at a_w below 0.6. Salt and sugar are commonly used to lower water activity by binding product moisture. In the recent years, there has been increased emphasis on reducing salt in processed foods. However, such changes should be systematically evaluated as salt reduction could potentially compromise microbiological safety and quality of the processed product (Doyle & Glass, 2010). Water activity of food material can also influence various chemical reactions. For example, non-enzymatic browning reactions increase with water activity level of 0.6–0.7a_w. Similarly, lipid oxidation can be minimized at about water activity level 0.2–0.3.

Table 1.2 Water activity values in different food products

Food product	Water activity, a_w
Fresh meat and fish	0.99
Bread	0.95
Cured ham, medium aged cheese	0.9
Jams and jellies	0.80
Plum pudding, fruit cakes, sweetened condensed milk, fruit syrups	0.80
Rolled oats, fudge, molasses, nuts, fondants	0.65
Dried fruit	0.60
Dried foods, spices, noodles	0.50
Marshmallow	0.6–0.65
Biscuits	0.30
Whole milk powder, dried vegetables, corn flakes	0.20
Instant coffee	0.20
English toffee	0.2–0.3
Hard candy	0.1–0.2

Compiled from various sources, including Fellows (2009), Heldman and Hartel (1998), and Potter and Hotchkiss (1998).

1.3.6 Reaction kinetics

During processing, the constituents of food undergo a variety of chemical, biological, physical, and sensory changes. Food scientists and engineers need to understand the rate of these changes caused by applying a given processing agent and the resulting modifications, so that they can control process operations to produce a product with the desired quality. Enzyme hydrolysis, browning, and color degradation are examples of chemical changes while inactivation of microorganisms after heat treatment is an example of a biological change. Food engineers rely on microbial and chemical kinetic equations to predict and control various changes happening in the processed food. Detailed discussion on kinetic changes in food processing systems is available elsewhere (Earle & Earle, 2012: Institute of Food Technologists (IFT), 2000). There is only a limited database on kinetics of destruction of variety of microorganisms, nutrients, allergens, and food quality attributes as a function of different thermal and non-thermal processing variables and more effort should be made to gather such information.

1.4 Common food preservation/processing technologies

1.4.1 Goals of food processing

The food industry utilizes a variety of technologies such as thermal processing, dehydration, refrigeration, and freezing to preserve food materials. The goals of these food preservation methods include eliminating harmful pathogens present in the food and minimizing or eliminating spoilage microorganisms and enzymes for shelf life extension.

The general concepts associated with processing of foods to achieve shelf life extension and preserve quality include (1) addition of heat, (2) removal of heat, (3) removal of moisture, and (4) packaging of foods to maintain the desirable aspects established through processing (Heldman & Hartel, 1998). Many food processing operations add heat energy to achieve elevated temperatures detrimental to the growth of pathogenic microorganisms. Exposure of food to elevated temperatures for a predetermined length of time (based on the objectives of the process at hand) is a key concept in food processing. Pasteurization of milk, fruit and vegetable juices, canning of plant and animal food products are some examples of processing with heat addition. The microbial inactivation achieved is based on exposure of foods to specific time-temperature combinations. Blanching is another example of heat addition, which helps with enzyme inactivation.

Processing of foods by heat removal is aimed more towards achieving shelf life extension by slowing down the biochemical and enzymatic reactions that degrade foods. Removal of moisture is another major processing concept, in which preservation is achieved by reducing free moisture in food to limit or eliminate the growth of spoilage microorganisms. Drying of solid foods and concentration of liquid foods fall under this category. Finally, packaging maintains the product characteristics established by processing of the food, including preventing postprocessing contamination. Packaging operations are also considered part of food processing.

In recent decades, the food industry has also investigated alternative lethal agents, such as electric fields, high pressure, irradiation, etc., to control microorganisms. Even though it is desirable that the preservation method by itself does not cause any damage to the food, depending upon the intensity of such agents, the quality of the food may also be affected.

Below are some key processing operations commonly used in the food industry. These and other food processing techniques are elaborated upon in various chapters of this book, for example, Chapter 3 (Separation and Concentration), Chapter 4 (Dehydration), Chapter 5 (Chilling and Freezing), Chapter 6 (Fermentation and Enzyme Technologies), Chapter 7 (Alternative and Emerging Food Processing Technologies), Chapter 8 (Nanotechnology), and Chapter 11 (Food Packaging).

1.4.2 Processes using addition or removal of heat

1.4.2.1 Pasteurization and blanching

Thermal pasteurization (named after inventor Louis Pasteur) is a relatively mild heat treatment, in which liquidds, semi-liquids or liquids with particulates are heated at a specific temperature (usually below 100 °C) for a stated duration to destroy the most heat-resistant vegetative pathogenic organisms present in the food. This also results in shelf life extension of the treated product. Different temperature-time combinations can be used to achieve pasteurization. For example, in milk pasteurization, heating temperatures vary widely, ranging from low-temperature, long-time heating (LTLT, 63 °C for a minimum of 30 min), to high-temperature, short-time heating (HTST, 72 °C for a minimum of 15 sec), to ultra-pasteurization (135 °C or higher for 2 sec to 2 min) (Singh & Heldman, 2009). In addition to destruction of pathogenic and spoilage microorganisms, pasteurization also achieves almost complete destruction of undesirable enzymes, such as lipase in milk. In recent years, the term "pasteurization" is also extended to destroying pathogenic microorganisms in solid foods (such as pasteurization of almonds through oil roasting, dry roasting, and steam processing).

The intensity of thermal treatment needed for a given product is also influenced by product pH; for example, fruit juices (pH <4.5) are generally pasteurized at 65 °C for 30 min, compared to other low-acid vegetables that need to be treated at 121 °C for 20–30 min. As a moderate heat treatment, pasteurization generally causes minimal changes in the sensory properties of foods with limited shelf life extension. Further, pasteurized products require refrigeration as a secondary barrier for microbiological protection.

Blanching, a mild thermal treatment similar in temperature-time intensity to pasteurization, is applied to fruit and vegetables to primarily inactivate enzymes that catalyze degradation reactions. This treatment also destroys some microorganisms. It is achieved by using boiling water or steam for a short period of time, 5–15 min or so, depending on the product. Other beneficial effects are color improvement and reducing discoloration. Blanching is often used as a pretreatment to thermal sterilization, dehydration, and freezing to control enzymes present in the food. Other benefits of blanching include removal of air from food tissue and softening plant tissue to facilitate packaging into food containers.

1.4.2.2 Thermal sterilization

Thermal sterilization involves heating the food to a sufficiently high temperature (>100 °C) and holding the product at this temperature for a specified duration, with the goal of inactivating bacterial spores of public health significance (Pflug, 1998). This is also known as canning or retorting. Prolonged thermal exposure during heating and cooling can substantially degrade product sensory and nutritional quality. Commercial sterility of thermally processed food, as defined by the US Food and Drug Administration (FDA), is the condition achieved by the application of heat that renders the food free of (i) microorganisms capable of reproducing in the food under normal non-refrigerated storage and distribution conditions, and (ii) viable microbial cells or spores of public health significance. Consequently, commercially sterile food may contain a small number of viable, but dormant, non-pathogenic bacterial spores. Traditionally, food processors use severe heat treatment to eliminate 12-log of *C. botulinum* spores (i.e. 12-D processes) to sterilize low-acid (pH ≥4.6) canned foods. Many canned foods have shelf lives of 2 years or longer at ambient storage conditions.

1.4.2.3 Aseptic processing

Aseptic processing, a continuous thermal process, involves pumping of pumpable food material through a set of heat exchangers where the product is rapidly heated under pressure to ≥130 °C to produce shelf-stable foods. The heated product is then passed through a holding tube, wherein the temperature of the product mixture is equilibrated and held constant for a short period as determined by the type of food and microbes present, and passes through set of cooling heat exchangers to cool the product. The sterilized cooled product is then aseptically packaged in a presterilized package (Sastry & Cornelius, 2002). Conventional aseptic processing technologies utilize heat exchangers such as scraped surface heat exchangers. Advanced food preservation techniques may utilize ohmic heating or microwave heating instead (Yousef & Balasubramaniam, 2013).

1.4.2.4 Sous-vide cooking

Sous-vide cooking involves vacuum packaging food before application of low-temperature (65–95 °C) heating and storing under refrigerated conditions (0–3 °C). Meat, ready meals, fish stews, fillet of salmon, etc. are some examples of sous-vide cooked products. This technology is particularly appealing to the food service industry, and has been adopted mainly in Europe. Due to use of modest temperatures, sous-vide cooking is not lethal enough to inactivate harmful bacterial spores. In addition, vacuum packaging conditions could also support potential survival of *Clostridium botulinum* spores.

1.4.2.5 Microwave heating

Microwave energy (300–300,000 MHz) generates heat in dielectric materials such as foods through dipole rotation and/or ionic polarization (Ramaswamy & Tang, 2008). In microwave heating, rapid volumetric heating could reduce the time required to achieve the desired temperature, thus reducing the cumulative thermal treatment time and better preserving the thermolabile food constituents. A household microwave oven uses the 2450 MHz frequency for microwave. For industrial application, a lower frequency of 915 MHz is selected for greater penetration depth. Microwave heating can be operated in both batch and continuous (aseptic) operations. Care must be taken to avoid non-uniform heating and overheating around the edges. In 2010, the FDA accepted an industrial petition for microwave processing of sweet potato puree that is aseptically packaged in sterile flexible pouches.

1.4.2.6 Ohmic heating

Ohmic heating involves electrical resistance heating of the pumpable food to rapidly heat the food material. The heat is generated in the form of an internal energy transformation (from electric to thermal) within the material as a function of an applied electric field (<100 V/cm) and the electrical conductivity of the food. Ohmic heating has been shown to be remarkably rapid and relatively spatially uniform in comparison with other electrical methods. Therefore, the principal interest has traditionally been in sterilization of those foods (such a high-viscosity or particulate foods) that would be difficult to process using conventional heat exchange methods (Sastry, 2008). Another application of ohmic heating includes improvement of extraction, expression, drying, fermentation, blanching, and peeling.

1.4.2.7 Drying

Drying is one of the oldest methods of preserving food. The spoilage microorganisms are unable to grow and multiply in drier environments for lack of free water. Drying is a process of mobilizing the water present in the internal food matrix to its surface and then removing the surface water by evaporation (Heldman & Hartel, 1998). Drying often involves simultaneous heat and mass transfer. Most drying operations involve changing free water present within the food to vapor form and removing it by passing hot air over the product.

During drying, the heat is transferred from an external heating medium into the food. The moisture within the food moves towards the surface of the material due to the vapor pressure gradient between the surface and interior of the product. The moisture is then evaporated into the heat transfer medium (usually air). The heat transfer can be accomplished through conduction, convection or radiation. While convective heat transfer is the dominant mechanism at the surface, heat is transferred through conduction within the food material. The moisture movement within the food material utilizes a diffusion process. There are several drying and dehydration methods frequently used in food processing such as hot air drying, spray drying, vacuum drying, freeze drying, osmotic dehydration, etc. During hot air drying, heat is transferred through the food either from heated air or from heated surfaces. Vacuum drying involves evaporation of water under vacuum or reduced pressures. Freeze drying involves removing the water vapor through a process called sublimation. Freeze drying helps to maintain food structure.

1.4.2.8 Refrigeration and freezing

Refrigeration and freezing have become an essential part of the food chain; depending on the type of product, they are used in all stages of the chain, from food processing, to distribution, retail, and final consumption at home. These two unit operations take away heat energy from food systems and maintain the lower temperatures throughout the storage period to slow down biochemical reactions that lead to deterioration. The food industry employs both refrigeration and freezing processes where the food is cooled from ambient to temperatures above 0 °C in the former and between −18 °C and −35 °C in the latter to slow the physical, microbiological, and chemical activities that cause deterioration in foods (Tassou et al., 2010).

Chilled or refrigerated storage refers to holding food below ambient temperature and above freezing, generally in the range of −2 to ~16 °C. Removing sensible heat energy from the product using mechanical refrigeration or cryogenic systems lowers the product temperature. Many raw products (such as milk and poultry) are rapidly chilled prior to further processing to minimize any microbial growth in the raw product. After cooking, foods are often kept under refrigerated conditions during storage and retailing. Many of the minimally processed foods (e.g. pasteurization) are promptly refrigerated to prevent growth of the microorganisms that survive processing.

For frozen storage, food products are frozen to temperatures ranging from −12 °C to −18 °C. Appropriate temperature control is important in freezing to minimize quality changes, ice recrystallization, and microbial growth. Food products can be frozen using either indirect contact or direct contact systems (Heldman & Hartel, 1998). In indirect contact systems, there is no direct contact between the product and the freezing medium. Cold air and liquid refrigerants are examples of freezing media used. Cabinet freezing, plate freezing, scraped surface heat exchanger, and indirect contact air-blast systems are different examples of indirect freezing equipment used in the industry. Direct contact freezing systems do not have a barrier between the product and the freezing medium. Direct contact air-blast, fluidized bed, immersion freezing, and spiral conveyor systems are examples of direct contact freezing.

1.4.3 Non-thermal food processing and preservation

During the past two decades, due to increased consumer interest in minimally processed foods with reduced preservatives, several non-thermal preservation methods have been investigated. These technologies often utilize lethal agents (such as pressure, irradiation, pulsed electric field, ultraviolet irradiation, and ultrasound, among others) with or without combination of heat to inactivate microorganisms (Zhang et al., 2011). This helps to reduce the severity of thermal exposure and preserve product quality and nutrients. Since the mechanism of microorganism inactivation by non-thermal lethal agents may be different from that of heat, it is important to understand the synergy, additive, or antagonistic effects of sequential or simultaneous combinations of different lethal agents. Irradiation, high-pressure processing, and pulsed electric field processing are examples of non-thermal processing methods that may be of commercial interest.

1.4.3.1 Irradiation

Irradiation is one of the most extensively investigated non-thermal technologies. Ionizing radiation includes γ-ray and electron beam. During irradiation of foods, ionizing radiation penetrates a food and energy is absorbed. Absorbed dose of radiation is expressed in grays (Gy), where 1 Gy is equal to an absorbed energy of 1 J/kg. Milder doses (0.1–3 kGy), called "radurization," are used for shelf life extension, control of ripening, and inhibition of sprouting. Radicidation is carried out to reduce viable non-spore forming pathogenic bacteria, using a dose between 3 and 10 kGy. Radappertization from 10 kGy to 50 kGy enables the sterilization of bacterial spores. From its beginning in the 1960s, the symbol Radura has been used to indicate ionizing radiation treatment (Figure 1.3).

Radiation is quite effective in penetrating through various packaging materials. However, the radiation dose may cause changes in packaging polymers. Thus, careful choice of packaging material is critical to avoid any radiolytic products from packaging contaminating the food products. Consumer acceptance is one of the barriers to widespread adoption of irradiation for food processing applications (Molins, 2001).

Figure 1.3 International Radura symbol for irradiation on the packaging of irradiated foods (from www.fsis.usda.gov/Fact_Sheets/Irradiation_and_Food_Safety/index.asp).

1.4.3.2 High-pressure processing

High-pressure processing, also referred to as "high hydrostatic pressure processing" or "ultra-high pressure processing," uses elevated pressures (up to 600 MPa), with or without the addition of external heat (up to 120 °C), to achieve microbial inactivation or to alter food attributes (Cheftel, 1995; Farkas & Hoover, 2000). Pressure pasteurization treatment (400–600 MPa at chilled or ambient conditions), in general, has limited effects on nutrition, color, and similar quality attributes. Uniform compression heating and expansion cooling on decompression help to reduce the severity of thermal effects such as quality degradation and nutritional loss encountered with conventional processing techniques. Figure 1.4 summarizes typical pressure and temperature levels for various food process operations. Examples of high-pressure pasteurized products commercially available in the US include smoothies, guacamole, deli meat slices, juices, ready meal components, poultry products, oysters, ham, fruit juices, and salsa.

Heat, in combination with pressure, is required for spore inactivation. This process is called pressure-assisted thermal processing (PATP) or pressure-assisted thermal sterilization (PATS). During PATP, preheated (70–85 °C) food material is subjected to a combination of elevated pressure (500–700 MPa) and temperature (90–120 °C) for a specified holding time (Nguyen & Balasubramaniam, 2011). PATP has shown better preservation of textural qualities in low-acid vegetable products. Minimal thermal exposure with a shorter pressure holding time helps to retain product textural quality attributes in comparison with conventional retort processing where the product experiences prolonged thermal exposure. In 2010, the FDA issued no objection to an industrial petition for

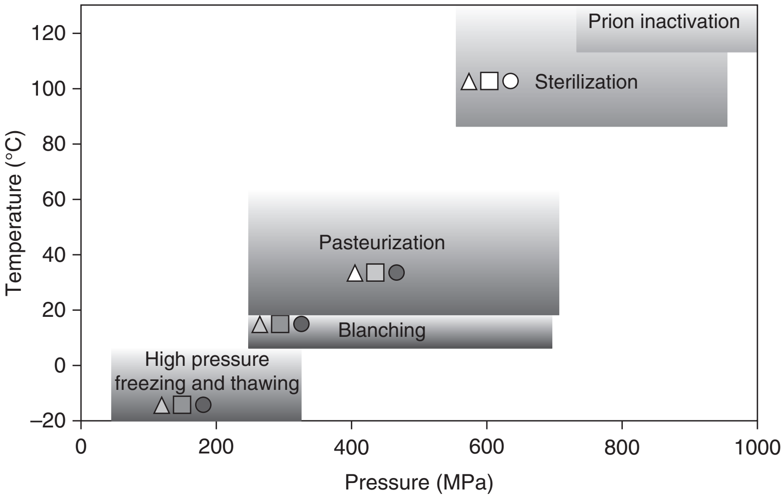

Figure 1.4 Different pressure-temperature regions yield different processing effects. Inactivation of vegetative bacteria, yeast, and mold (□), bacterial spores (○), and enzymes (Δ) is also shown. A filled symbol represents no effect, an open symbol represents inactivation. Adapted from Nguyen and Balasubramaniam (2011).

sterilizing low-acid mashed potato product through pressure-thermal sterilization.

1.4.3.3 Pulsed electric field processing

During pulsed electric field (PEF) processing, a high-voltage electrical field (20–70 kV/cm) is applied across the food for a few microseconds. A number of process parameters including electric field strength, treatment temperature, flow rate or treatment time, pulse shape, pulse width, frequency, and pulse polarity govern the microbiological safety of the processed foods. Food composition, pH, and electrical conductivity are parameters of importance to PEF processing. During PEF treatment, the temperature of the treated foods increases due to a electrical resistance heating effect. This temperature increase can also contribute to the inactivation of microorganisms and other food quality attributes. The technology effectively kills a variety of vegetative bacteria, but spores are not inactivated at ambient temperatures (Yousef & Zhang, 2006; Zhang et al., 1995). Typical PEF equipment components include pulse generators, treatment chambers, and fluid-handling systems, as well as monitoring and control devices. PEF technology has the potential to pasteurize a variety of liquid foods including fruit juices, soups, milk, and other beverages.

1.4.3.4 Ultrasound

High-power ultrasound processing or sonication is another alternative technology that has shown promise in the food industry (Piyasena et al., 2003), especially for liquid foods, in inactivating spoilage microorganisms. Ultrasound is a form of energy generated by sound waves of frequencies above 16 kHz; when these waves propagate through a medium, compressions and depressions of the medium particles create microbubbles, which collapse (cavitation) and result in extreme shear forces that disintegrate biological materials. Sonication alone is not very efficient in killing bacteria in food, as this would need an enormous amount of ultrasound energy; however, the use of ultrasound coupled with pressure and/or heat is promising (Dolatowski et al., 2007; Piyasena et al., 2003).

1.4.4 Redefining pasteurization

Successful commercial introduction of a number of non-thermal pasteurized products prompted the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) to suggest a new definition for pasteurization (National Advisory Committee on Microbiological Criteria for Foods, 2006). According to NACMCF recommendations, pasteurization is defined as "any process, treatment, or combination thereof, that is applied to food to reduce the most resistant microorganism(s) of public health significance to a level that is not likely to present a public health risk under normal conditions of distribution and storage." High-pressure and PEF processing, ultraviolet processing, γ-irradiation, and other non-thermal processes are examples of processes that potentially satisfy the new definition of pasteurization.

1.5 Other food processing/preservation technologies

1.5.1 Fermentation

Fermentation causes desirable biochemical changes in foods in terms of nutrition or digestion, or makes them safer or tastier through microbial or enzyme manipulations. Examples of fermented foods are cheese, yogurt, most alcoholic beverages, salami, beer, and pickles. Representative vegetative bacteria in the fermentations are *Lactobacillus*, *Lactococcus*, *Bacillus*, *Streptococcus*, and *Pseudomonas* spp. Yeast and fungi (e.g. *Saccharomyces, Endomycopsis*, and *Monascus*) are also used for fermentation. Food supports controlled growth of these microorganisms, which modify food properties (texture, flavor, taste, color, etc.) via enzyme secretion.

1.5.2 Extrusion

Extrusion is a process that converts raw material into a product with a desired shape and form, such as pasta, snacks, textured vegetable protein, and ready-to-eat cereals, by forcing the material through a small opening using pressure (Singh & Heldman, 2009). Some of the unique advantages of extrusion include high productivity, adaptability, process scale-up, energy efficiency, low cost, and zero effluents (Riaz, 2000). An extruder consists of a tightly fitting screw rotating within a stationary barrel. Within the extruder, thermal and shear energies are applied to a raw food material to transform it to the final extruded product. Preground and conditioned ingredients enter the barrel where they are conveyed, mixed, and heated by a variety of screw and barrel configurations. Inside the extruder, the food may be subjected to several unit operations, including fluid flow, heat transfer, mixing, shearing, size reduction, and melting. The product exits the extruder through a die, where it usually puffs (if extruded at >100 °C and higher than atmospheric pressure) and changes texture from the release of steam and normal forces (Harper, 1979). Extruded products may undergo a number of structural, chemical, and nutritional changes including starch gelatinization, protein denaturation, lipid oxidation, degradation of vitamins, and formation of flavors (Riaz, 2000). Very limited studies are available to describe kinetics changes in foods during extrusion (Zhao et al., 2011).

1.5.3 Baking

Baking uses dry heat to cook fully developed flour dough into a variety of baked products including bread, cake, pastries, pies, cookies, scones, crackers, and pretzels. The dough needs to undergo various stages (mixing, fermentation, punching/sheeting, panning, proofing among others) before it is ready for baking.

Carbon dioxide gas is produced from yeast fermentation of available sugars, which could either be added or obtained via amylase breakdown of starch. During baking, heat from the source in an oven is transferred to the dough surface by convection; from the surface, it then transfers via conduction. As the heat is conducted through the food, it transforms the batter or dough into a baked food with a firm crust and softer center. During baking, heat causes the water to vaporize into steam. Gelatinization of flour starch in the presence of water occurs. The protein network (gluten) holds the structure, while carbon dioxide gas, that gives the dough its rise, collapses during baking (at ~450 °C). The product increases in size and volume, called leavening. Baking temperatures also cause a number of biochemical changes in the batter and dough, including dissolving sugar crystals, denaturing egg and gluten proteins, and gelatinizing starch. Baking also causes the surface to lose water, and breaks down sugars and proteins on the surface of the baked goods. This leads to formation of a brown color and desired baked flavor (Figoni, 2010).

1.5.4 Hurdle technology

Hurdle technology involves a suitable combination of different lethal agents to ensure microbial safety, quality, and stability of the processed product. Heat, pressure, acidity, water activity, chemical/natural preservatives, and packaging are examples of hurdles that can be combined to improve the quality of the final processed product. The hurdle approach requires the intensity of individual lethal agents (for example, heat or pressure) to be relatively modest, yet is quite effective in controlling microbial risk. Efforts must be made to understand the potential synergistic, additive or antagonistic effects of combining different lethal agents during hurdle technology.

1.5.5 Packaging

Packaging plays a vital role in many food preservation operations. Packaging has many functions, including containment, preservation, communication/education, handling/transportation, and marketing. Packaging helps maintain during storage the quality and properties of foods attained via processing. The packaging protects the food material from microbiological contaminants and other environmental factors. The package also helps prevents light-induced changes in stored food products and minimizes loss of moisture.

Depending upon the intensity of lethal treatments (heat, pressure, radiation dose), processing not only affects the food material but also alters the (moisture and oxygen) barrier properties of packaging materials and possibly induces migration of polymer material into the food. Thus, careful choice of food packaging material is essential for successful food process operation.

1.6 Emerging issues and sustainability in food processing

Modern food processing was developed during the 19th and 20th centuries with the rise of thermal pasteurization and sterilization techniques with the view of the extending shelf life of processed foods. Developments in industrial food processing technologies ensured the availability of a safe, abundant, convenient food supply at reasonable prices. However, the industry is currently undergoing a transformation in response to a variety of societal challenges. In a recent IFT scientific review, Floros et al. (2010) identified three emerging societal issues that will likely shape future developments in food processing.

- **Feeding the world**. The world population today is about 6.8 billion and it is expected to reach about 9 billion by 2050. Sustainable and efficient industrial food processing technologies at reasonable cost are needed to feed this ever-expanding world population.
- **Overcoming negative perceptions about "processed foods**." There has been an increased negative perception towards processed foods in the US. A number of societal factors have contributed to this trend, including negative perceptions towards technology use, diminishing appreciation of scientific literacy, as well as lack of familiarity or appreciation about farming among increasingly urban-based consumers.
- **Obesity**. Overweight and obesity are major health problems in the US and developed countries. Overconsumption of calorie-dense processed food and sedentary consumer lifestyles are some reasons put forward for the increase in obesity.

Apart from these issues, sustainability in the food processing industry is another emerging key societal issue. Sustainability is the capacity to endure; it is utilizing natural resources so that they are not depleted or permanently damaged. Water, land, energy, air, etc. are resources utilized in agriculture and food processing. Environmental concerns related to food production and processing which require consideration include land use change and reduction in biodiversity, aquatic eutrophication by nitrogenous factors and phosphorus, climate change, water shortages, ecotoxicity, and human effects of pesticides, among others (Boye & Arcand, 2013). Sustainable food processing technologies emphasize the efficient use of energy, innovative or alternative sources of energy, less environmental pollution, minimal use of water, and recycling of these resources as much as possible. Sustainable food processing requires processors to maximize the conversion of raw materials into consumer products by minimizing postharvest losses and efficient use of energy and water. Modern food processing plants can contribute to sustainability by utilizing green building materials and practices in their construction, utilizing innovative building designs, using energy-efficient equipment and components, and following efficient practices in routing, storing, and processing of ingredients and distribution and handling of finished products. Most of the food processing operations described in subsequent chapters of this textbook include a short discussion on sustainability.

1.7 Conclusion

Modern food processors can choose from several preservation approaches (heat addition or removal, acidity, water activity, pressure, electric field, among others) to transform raw food materials to produce microbiologically safe, extended shelf life, consumer-desired, convenient, value-added foods. Successful food processing requires integration of knowledge from several disciplines including engineering, chemistry, physics, biology, nutrition, and sensory sciences. The type of food processing operation chosen can influence the extent of changes in product quality (color, texture, flavor) attributes. The extent of nutrient and quality retention in processed food depends upon intensity of treatment applied, type of nutrient or food quality attribute, food composition, and storage conditions.

While industrial food processing provides safe, plentiful, relatively inexpensive food, processed foods are often perceived as unhealthy and not sustainable. Developments in novel "non-thermal" technologies that rely on lethal agents other than heat (pressure, electric field, among others) may partly address this issue by increasing nutrient bioavailability and preserving heat-sensitive phytochemicals. Efforts must be made to introduce lean manufacturing concepts developed in other industries to food processing to reduce energy and water use and allow the production of healthy processed foods at affordable cost.

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