18

Drying and Food Preservation

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CONTENTS

18.1 Introduction

18.1.1 Background of Drying

The preservation of foods by drying is the time-honored and most common method used by humans and the food processing industry. Dehydration of food is one of the most important achievements in human history, making humans less dependent upon a daily food supply even under adverse environmental conditions [34]. Though in earlier times drying was dependent on the sun, nowadays many types of sophisticated equipment and methods are used to dehydrate foods. During the past few decades, considerable efforts have been made to understand some of the chemical and biochemical changes that occur during dehydration, and develop methods for preventing undesirable quality losses. Foods can be divided into three broad groups based on the value added through processing by drying. In the case of cereals, legumes, and root crops, very little value is added per kilogram processed. More value per unit mass is added to foods such as vegetables, fruits, and fish; and considerably more to high-value crops such as spices, herbs, medicinal plants, nuts; bioactive materials; and enzymes [7].

18.1.2 Mode of Preservation

Drying reduces the water activity, thus preserving foods by avoiding microbial growth and deteriorative chemical reactions. The effects of heat on microorganisms and the activity of enzymes are also important in the drying of foods. In the case of foods to be preserved by drying, it is important to maximize microorganism and enzyme inactivation for preventing spoilage and enhancing safety, and reduce the components responsible for the deterioration of the dried foods. Also, in the case of drying bacterial cultures, enzymes, or vitamins, minimum inactivation of the microorganism and enzyme is required. Thus, detrimental effects of drying may be desirable or undesirable, depending on the purpose of the drying process.

18.1.3 State of Water in Foods

The terms dried and dehydrated are not synonymous. The U.S. Department of Agriculture lists dehydrated foods as those with no more than 2.5% water (dry basis), while the term dried foods applies to any food product with more than 2.5% water (dry basis) [144]. The concept of bound water and free water has been developed from drying principles, and it is important for dried products – for its stability during processing and storage. A product containing no water is termed as bone-dry. Water exists in foods in different forms or states. In foods, water having properties different from those of pure water can be defined as bound water. In the literature, different forms of bound water are defined [101], for example, unfreezable, immobile, monolayer, and nonsolvent water. However, the fraction of bound water depends on its definition and the measurement technique used [101]. The binding energy of different states of bound water affects the drying process, since it requires more energy to remove bound water than free water.

18.1.4 End Point of Drying

Equilibrium in drying system is the ultimate endpoint for the process. Water activity is commonly used to estimate the equilibrium point in the case of thermal- and osmotic-drying processes. In mechanical dewatering, the magnitude of the applied force and rheological properties of the foods affect the equilibrium point. Generally meat, fish, and dairy products are dehydrated to a moisture content of 3% or less, vegetable products usually to 5%, and cereal products frequently to as much as 12% [118]. A maximum moisture level is usually established for each dried product separately, based on the desired quality after drying and during storage. Different attributes of quality can be targeted; thus, the endpoint should be determined from all aspects, such as safety first and then consumer acceptance.

18.1.5 Heating Methods in Drying

Heating air using either an electric heater or flue gas is the conventional heating method used for drying foods. In this case, heat transfer from the gas to the product occurs mainly through convection. The heating method is another important aspect of drying, in terms of quality as well as energy cost. Microwave, infrared, radio frequency, refractance window, and dielectric heating use electromagnetic wavelength spectrum as a form of energy, which interacts with the materials, thus generating heat and increasing the drying rate dramatically. Dielectric drying uses frequencies in the range of 1–100 MHz, whereas microwave drying uses frequencies in the range of 300–300,000 MHz. Microwave heating is rapid, more uniform in the case of liquids, and more energy efficient than the hot-air method [28]. Applying microwave energy under vacuum affords the advantages of both vacuum drying and microwave drying, thereby providing improved energy efficiency and product quality. The energy can be applied in pulsed or continuous mode; however, pulsed microwave drying is more efficient than continuous drying. The use of electrotechnology in drying is gaining priority in the food industry to improve drying efficiency as well as quality.

18.2 Drying Methods

Drying processes can be broadly classified, based on the water-removing method applied, as (a) thermal drying, (b) osmotic dehydration, and (c) mechanical dewatering. In thermal drying, a gaseous or void medium is used to remove water from the material. Thus, thermal drying can be divided further into three types: (a) air drying, (b) low air environment drying, and (c) modified atmosphere drying. In osmotic dehydration, a solvent or solution is applied to remove water, whereas in mechanical dewatering physical force is used. Consideration should be given to many factors before selecting a drying process. These factors are (a) the type of product to be dried, (b) desired properties of the finished product, (c) allowable temperature tolerance, (d) the product's susceptibility to heat, (e) pretreatments required, (f) capital and processing costs, and (g) environmental factors. There is no one best technique of drying that is applicable for all products [25,144].

18.3 Thermal Drying

Thermal drying is one of the most widely used methods of drying foods. In this process, heat is mainly used to remove water from the foods. The mechanisms of moisture transfer depend mainly on the types or physicochemical state of food materials and the drying process. Food materials can be classified as (a) homogeneous gels, (b) porous materials with interconnecting pores or capillaries, and (c) materials having an outer skin that is the main barrier to moisture flow [27]. The type or structure of foods always plays an important role in the drying process.

18.3.1 Drying Fundamentals

In terms of transport phenomenon, it is considered as both heat and mass transport process inside and outside of the food materials. Hence there are two resistances: heat transfer and mass transfer. During the *constant rate period,* it is considered that there exists a thin film of water on the slice and there is no internal or external mass transfer resistance. Hence, drying is controlled by external heat transfer. In the *falling rate period,* drying is controlled by the internal mass transfer resistance. The absence of a constant rate period indicates that the drying is controlled from the beginning by internal mass transfer resistance. The moisture content at the point when the drying period changes from a constant to a falling rate can be considered as the critical moisture content. The critical moisture content depends on the characteristics of the food and the drying conditions. The critical moisture contents varied from 0.78 to 0.83 (kg/kg, wet basis) for vegetables and 0.85 to 0.89 (kg/kg, wet basis) for fruits [119]. At high moisture content, liquid flow due to capillary forces dominates. At decreasing moisture content, the amount of liquid in the pores also decreases and a gas phase is built up, causing a decrease in liquid permeability. Gradually, the mass transfer is taken over by vapor diffusion in a porous structure. At the saturation point, liquid is no longer available in the pores and mass transfer is taken over completely by vapor diffusion [26].

The moisture is transferred from the solid materials by diffusion or capillary mechanism. In diffusion mechanism, the concentration gradient is the driving force. Water diffusion can be in the form of liquid or vapor. In the case of liquid diffusion, osmotic pressure could be the driving force for water movement. In capillary mechanism, the moisture moves due to surface tension and does not conform to the laws of diffusion. A porous material contains a complicated network of interconnecting pores and channels extending to the exterior surface. As water is removed, a meniscus is formed across each pore, which sets up capillary forces by the interfacial tension between the water and the solid. Capillary forces act in a direction perpendicular to the surface of the solid. It has been suggested that a combined mechanism of capillary forces and vapor diffusion is responsible for moisture movement in the drying of potato [39,40]. The drying experiments of Saravacos and Charm [119] with surface-active agents failed to show any important capillary forces during the dehydration of potatoes and other vegetables. Surfactants are known to reduce the surface tension of water, thus increasing the capillary forces in porous materials. Therefore, capillary flow is not significant in the vegetables studied by Saravacos and Charm [119]. Waananen and Okos [146] showed that during drying of pasta at a temperature close to the boiling point, liquid flow dominates moisture transport at high moisture levels and vapor flow is significant only at low moisture levels. Achanta and Okos [3] reviewed the shrinkage of different biopolymers and concluded that shrinkage on drying is equal to the volume of moisture leaving; thus, it is conceptually difficult to justify that capillary flow is important during the drying of high-moisture biopolymers.

The strength of capillary forces at a given point in a pore depends on the curvature of the meniscus, which is a function of the pore cross section. Small pores develop greater capillary forces than large ones; thus, large pores tend to empty their water content first [76]. In large pores, the capillary forces are small. The force of gravity is large in comparison with the capillary forces, and there is a directional effect due to gravity [76].

18.3.1.1 Drying Curve

Drying curve usually plots the drying rate versus drying time or moisture contents. Three major stages of drying can be observed in the drying curve (Figures 18.1 and 18.2):

1. Transient early stage, during which the product is heating up (transient period)
2. Constant or first period, in which moisture is comparatively easy to remove (constant rate period)
3. Falling or second period, in which moisture is bound or held within the solid matrix (falling rate period)

Typical drying rate curves are shown in Figures 18.1 and 18.2. The moisture content at which the change from the first to the second period occurs is known as the critical moisture content. Typically, two falling rate periods are observed for both hygroscopic and nonhygroscopic solids [138]. The first falling rate period is postulated to depend on both internal and external mass transfer rates; while the second period, during which drying is much slower, is postulated to depend entirely on internal mass transfer resistance. The slower rate may be due to the solid–water interaction or glass–rubber transition [3].

The drying behaviors of food materials depend on the porosity, homogeneity, and hygroscopic properties. The immediate entrance into the falling rate is characteristic of hygroscopic food materials. Lee et al. [68] studied the effect of sodium sulfate on the surface evaporation of a porous medium during the constant rate

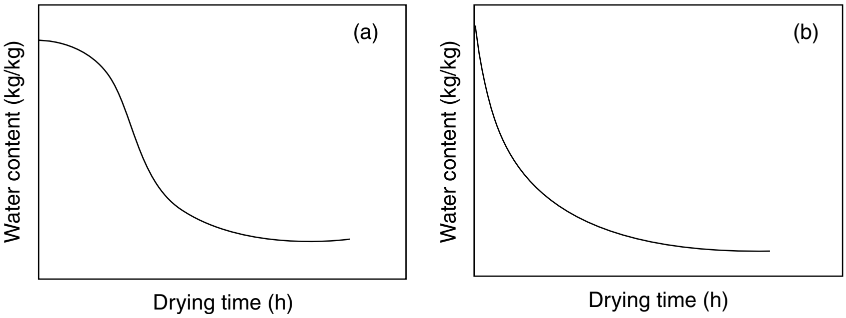

FIGURE 18.1 Typical drying curves (water content versus drying time): (a) with a lag period, (b) without a lag period.

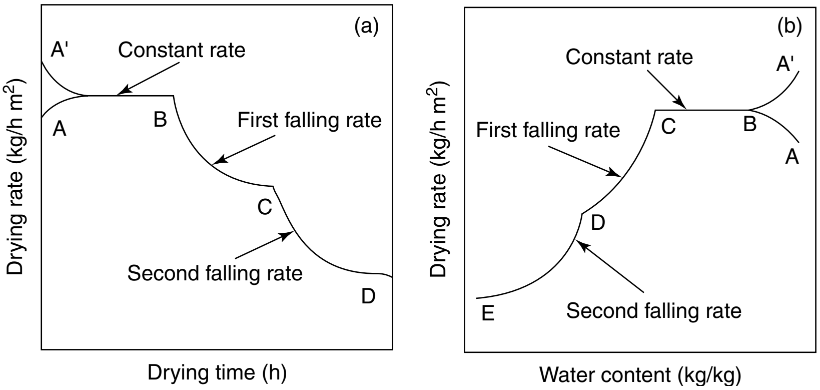

FIGURE 18.2 Typical drying rate curves: (a) drying rate versus drying time, (b) drying rate versus water content.

period. The drop in the drying rate was significant due to the decrease of surface vapor pressure and the change of liquid surface curvature due to meniscus effects by surface tension.

18.3.1.2 Energy Aspect of Air Drying

Drying is one of the most energy-intensive processes in the food industry. Apart from the rise of energy costs, legislation on pollution and sustainable and environment-friendly technologies created greater demand for energy-efficient drying processes in the food industry. Thus, novel thinking in the technology of drying methods and dryer design is evident. The food industry could save much money by avoiding costly energy waste. Improving energy efficiency by only 1% could result in as much as 10% increase in profits [12]. Conducting an energy survey is the traditional way to approach the problem. The energy survey analyzes the energy defect level at each stage of processing and strategies for their remedy [12].

18.3.1.3 Energy Losses in Air Drying

Heat losses during drying can be grouped into heat loss with the exhaust air, heat loss with the product, radiation heat loss from the dryer, heat loss due to leakage of air from the dryer, and heat loss due to overdrying of products. Table 18.1 shows the possible energy savings for walnut dehydration. Recirculating exhaust air in grain dryers is popular because of its effect on grain quality and energy conservation benefit. The high-humidity air damages grains to a lesser extent than low-humidity air.

Grains are severely damaged by high drying temperatures [130]. Thus, by changing the dryer design, energy losses can be avoided while achieving higher product quality. Energy can be saved by (a) reducing drying time or increasing throughput (better control), (b) avoiding heat losses, and (c) heat recovery from exhaust gas and dried product. The potential for energy conservation by design and changes in drying operation is significant. Strumillo and Lopez-Cacicedo [134] reviewed most of the methods of energy recovery from exhaust air, including heat exchangers (pipe and plate types), thermal wheel, heat pipe installation, and runaround coil. These methods recover mainly sensible heat from the exhaust, while most of the heat is lost with the latent heat of water vapor in the exhaust air. This latent heat can be recovered by condensing out water using a refrigeration system. However, a refrigeration system will consume extra power before further use. Among these methods, the heat pump dryer (using a dehumidifier) has a high potential for use in the food industry (discussed later).

TABLE 18.1

Energy Savings for Walnut Dehydration

Method	Possible Savings (%)
Preventing overdrying	25–33
Recirculation of drying air	25
Reducing airflow rate	≤25
Improved burner design and operation	≤10
Insulation of drying	3–4

Source: Strumillo, C. and Lopez-Cacicedo, C. 1987. In: Handbook of Industrial Drying. Mujumdar, A.S., Ed. Marcel Dekker, NY. pp. 823–862.

The broad classes of thermal drying are air drying, low air environment drying, and modified atmosphere drying.

18.3.2 Air-Drying Methods

In the case of air drying, atmosphere is used as the drying medium and heat as different modes could be applied in the process.

18.3.2.1 Sun Drying

Earlier, only sun drying was used for drying. In this process, foods are directly exposed to the sun by placing them on the land or left hanging in the air. The main disadvantages of this type of drying are (i) contaminations from the environment, (ii) product losses and contaminations by insects and birds, (iii) floor space requirements, (iv) difficulty in controlling the process, and (v) bad odor. When the climate is not particularly suitable for air drying or better quality is desired, mechanical air drying is mainly used. However, sun drying is the cheapest method of drying foods. Nowadays, solar and mechanical air drying is widely used commercially.

18.3.2.2 Solar Drying

Solar drying is an extension of sun drying that uses radiation energy from the sun. Solar drying is a nonpolluting process and uses renewable energy. Moreover, solar energy is an abundant energy source that cannot be monopolized [55]. However, solar drying has several drawbacks that limit its use in large-scale production. These are the need for large areas of space and for high labor inputs, difficulty in controlling the rate of drying, and insect infestation and microbial contamination [25,55]. More options in designing are now available in the literature in order to avoid or reduce the above difficulties. Sablani et al. [117] studied the performance of open rack, multirack dome dryer, and cabinet drier with convection air flow created with fan operated by solar battery. In addition to the dryer performance, quality attributes of dried sardines were assessed by determining yeast, mold, and bacterial counts; peroxide value; and color. A significant variation in drying rates and quality attributes was observed. Dome drying could use the multirack tray in a big dome for increasing the floor space for high loading, efficient use of energy, and better control of the process.

18.3.2.3 In-Store Drying

In-store drying can also be called low-temperature in-bin drying. It may be used when grains are stored until milled or sold. Weather conditions in tropical climates are less favorable for in-store drying, due to high ambient temperatures and relative humidity values. Two-stage drying can produce good quality by preventing discoloration of high-moisture grains and reduced cracking of skin dry kernels.

18.3.2.4 Convection Air Drying

Cabinet- and bed-type dryers (i.e., kiln, tray, truck tray, rotary flow conveyor, and tunnel) fall into the first generation [144]. This is the simplest drying technique, which takes place in an enclosed and heated chamber. The drying medium, hot air, is allowed to pass over the product, which has been placed in open trays. Convection drying is often a continuous process and is mostly used for products that are relatively low in value. Air drying is usually accomplished by passing air at regulated temperature and humidity over or through the food in a dryer. Factors that affect the rate of drying are temperature, humidity, air velocity and distribution pattern, air exchange, product geometry and characteristics, and thickness. The sample is usually placed on mesh trays in one layer or in bulk on a bed or hung from a string for better air circulation over the product. Air circulation can be horizontal or vertical to the layer or bed. The structure and composition, such as fat content, of a product affects the drying rate. In general, the hotter is the air temperature, the faster is the drying rate; and similarly, the higher is the velocity, the higher is the drying rate; the lower is the air humidity, the higher is the drying rate. The relative humidity (a measure of dryness) is lower when air temperature is raised. A dryer must expel air to get rid of moisture, thereby allowing new, lower humidity air to enter the system. However, this process causes heat loss from the dryer. In many cases, two- or multistage drying with different conditions could be used, for example, initial drying at 90°C and then the second or final stage at 60°C.

18.3.2.5 Explosive Puff Drying

Explosive puff drying uses a combination of high temperature and high pressure, and a sudden release of the pressure (explosion) to flush superheated water out of a product. This method gives a product of good rehydrability. However, the high heat can degrade food quality, and the explosion puffing may compromise product integrity [25].

18.3.2.6 Spray Drying

Spray drying is used to remove water from a free-flowing liquid mixture, thus transforming it into a powder form. The fluid to be dried is first atomized by pumping it through either a nozzle or a rotary atomizer, thus forming small droplets with large surface areas. The droplets immediately come into contact with a hot drying gas, usually air. The liquid is very rapidly evaporated, thus minimizing contact time and heat damage. Disadvantages include the size of the equipment required to achieve drying is very large and very oily materials might require special preparation to remove excessive levels of fat before atomization [25]. Ultrasonication in the chamber can be used instead of complex atomization to produce small-diameter droplets in spray drying.

18.3.2.7 Fluidized Bed Drying

This technique involves the movement of particulate matter in an upward-flowing gas stream, usually hot air. Fluidization mobilizes the solid particulates, thus creating turbulences on the solid surfaces, which increases the drying rate. The hot gas is introduced at the bottom of a preloaded cylindrical bed and exits at the top. In some cases, a vibratory mechanism is used to increase the contact of the product with the hot gas. Fluidized bed drying is usually carried out as a batch process and requires relatively small, uniform, and discrete particles that can be readily fluidized [25]. The main advantages of fluidized bed drying are uniform temperature and high drying rates, thus less thermal damage. A rotating chamber is also used with the fluidized bed, thus increasing centrifugal force to further increase the drying rate and mixing. The use of a solid carrier, such as sea sand, and wheat bran could prevent the biomaterial from deterioration due to thermal shock [88].

18.3.2.8 Spouted Bed Drying

In a spouted bed dryer, a jet of heated gas enters the chamber at the center of a conical base. The food particles are rapidly dispersed in the gas, and drying occurs in an operation similar to flash drying. This works very well with large pieces that cannot be dried in a fluidized bed dryer [25].

18.3.2.9 Ball Drying

In this method, the material to be dried is added at the top of the drying chamber through a screw conveyor. The material within the drying chamber comes into direct contact with heated balls made from ceramic or other heat-conductive material. Drying occurs primarily by conduction. Hot air is passed through the bottom side of the chamber. When the product arrives at the bottom of the chamber, it is separated from the balls and collected [25].

18.3.2.10 Rotary Drum Drying

Rotary drum dryers are cylindrical shells 1–5 m in diameter, 10–40 m in length, and rotating at 1–8 rpm with a circumferential speed of approximately 0.2–0.4 m/s. These conditions depend on the product types to be dried. The dryers are designed to operate at a nearly horizontal position, inclined only by 2°–6° to maintain the axial advance of solids, which are fed from the upper end of the dryer body [94].

18.3.2.11 Drum Drying

This technique removes water from a slurry, paste, or fluid that has been placed on the surface of a heated drum. The dryer may comprise either a single or a double drum. Drum drying is typically a continuous operation, and care must be taken to ensure that the product that is to be dried adheres well to the drying surface; in some cases, it may be necessary to modify the liquid product by using additives to change its surface tension or viscosity [25].

18.3.3 Low Air Environment Drying

18.3.3.1 Vacuum Drying

Vacuum drying of food involves subjecting the food to a low pressure and a heating source. The vacuum allows the water to vaporize at a lower temperature than at atmospheric conditions, thus foods can be dried without exposure to high temperature. In addition, the low level of oxygen in the atmosphere diminishes oxidation reactions during drying. In general, color, texture, and flavor of vacuum-dried products are improved compared with air-dried products. In some cases, the product is comparable to the quality of freeze-dried foods.

18.3.3.2 Freeze Drying

In freeze drying, frozen material is subjected to a pressure below the triple point (at 0°C, pressure: 610 Pa) and heated to cause ice sublimation to vapor. A schematic diagram of the different states of water with triple point is shown in Figure 18.3. This method is usually used for high-quality dried products, which contain heat-sensitive components such as vitamins, antibiotics, and microbial culture. The virtual absence of air and low temperature prevents deterioration due to oxidation or chemical modification of the product. It also gives very porous products, which results in high rehydration rates. However, freeze drying is a slow and expensive process. A long processing time requires additional energy to run the compressor and refrigeration units, which makes the process very expensive for commercial use. Thus, it is mainly used for high-value products [25].

18.3.3.3 Heat Pump Drying

The heat pump dryer is a further extension of the conventional convection air dryer with an inbuilt refrigeration system (Figure 18.4). Dry heated air is supplied continuously to the product to pick up moisture. This humid air passes through the evaporator of the heat pump where it condenses, giving up its latent heat of vaporization to the refrigerant in the evaporator. This heat is used to reheat the cool dry air passing over the hot condenser of the heat pump. Thus, the latent heat recovered in the process is released at the condenser of the refrigeration circuit and used to reheat the air within the dryer. The use of the heat pump dryer offers several advantages over conventional hot air dryers for drying food products, including higher energy efficiency, better product quality, the ability to operate independent

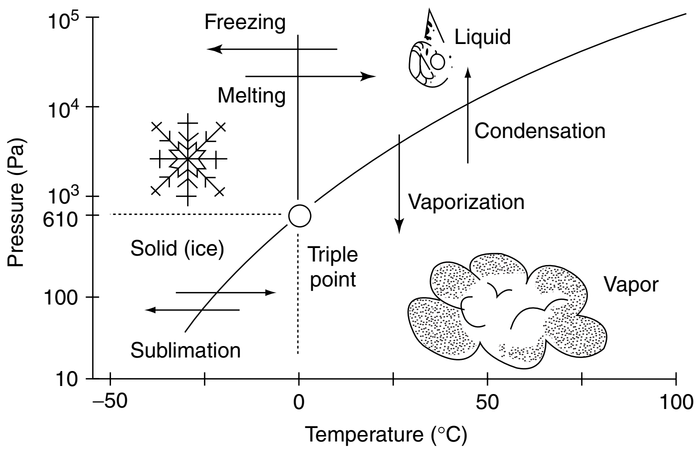

FIGURE 18.3 Schematic diagram of the different states of water showing triple point. (From Nijhuis, H. H. et al. 1996. *Drying Technol.* 14: 1429–1457.)

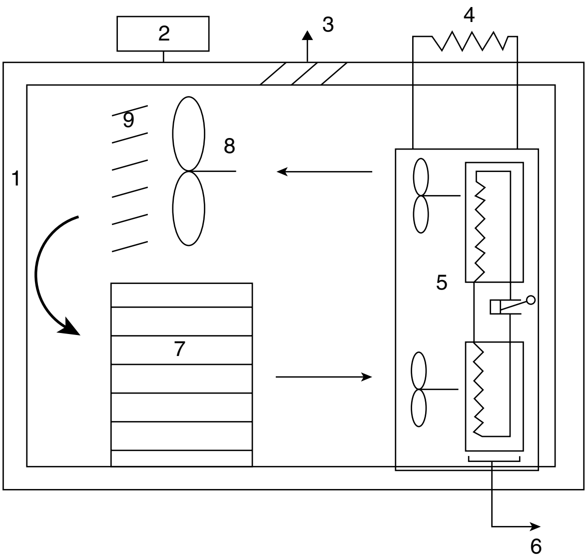

FIGURE 18.4 A schematic diagram of the operation of a typical heat pump dryer: (1) vapor-sealed and insulated structure, (2) humidifier, (3) overheat vent, (4) external condenser, (5) heat pump dehumidifier, (6) condensate, (7) product tray, (8) primary air circulation fan and (9) air distributor. (From Perera, C. O. and Rahman, M. S. 1997. *Trends Food Sci. Technol.* 8(3): 75.)

of outside ambient weather conditions, and zero environmental impact. In addition, the condensate can be recovered and disposed of in an appropriate manner, and there is also the potential to recover valuable volatile components from the condensate [90]. One of the main reasons of quality improvements in heat pump dried products is due to its ability to operate at low temperatures. If a heat pump dryer is used at low temperatures (10°C–60°C) for highly perishable food products, adequate precautions need to be taken. There is also potential to use heat pump drying with modified atmospheres to obtain better quality products.

18.3.3.3.1 Quality Improvement

A major advantage of using heat pump drying is the potential improvements in the quality of the products dried under optimum drying conditions. Usually, dried products have low volatile-aroma content, suffer a loss of heat-labile vitamins, and have a high incidence of color degradation. Ginger dried in a heat pump dryer was found to retain over 26% of gingerol, the principal volatile flavor component responsible for ginger's pungency, compared to only about 20% in rotary-dried commercial samples [75]. The higher volatile content retention in heat pump-dried samples may be due to reduced degradation of gingerol at the lower drying temperature used compared with the commercial dryer temperatures. The loss of volatiles varies with concentration, with the greatest loss occurring during the early stages of drying when the initial concentration of the volatile components is low. Since heat pump drying is conducted in a sealed chamber, any compound that volatilizes will remain within it, and the partial pressure for that compound will gradually build up within the chamber, retarding further volatilization from the product [90].

Development of a brown center sometimes occurs in macadamia nuts if high-moisture nuts are dried at elevated temperatures [98]. Van Blarcom and Mason [142] found that heat pump drying of macadamia nuts did not result in the above defect, even when they were dried at 50°C. Mason [74] studied the heat pump drying of macadamia kernels and herbs, at temperature and relative humidity ranges of 30°C–50°C and 0.10–0.50, respectively. Freshly harvested macadamia nuts can be dried rapidly up to a moisture content of 0.015 with no loss in quality when dried under the conditions mentioned above. This may be due to the faster drying rates associated with the heat pump drying process [90]. The losses in color, flavor, and nutritive value associated with dried products are attributed to nonenzymatic browning. It is recognized that the rate of reaction for nonenzymatic browning in dried products is highest at moisture levels that are commonly attained toward the end of the drying cycle, when the drying rate is low and the product temperature approaches that of the drying medium. However, the lower drying temperatures used throughout the drying cycle in heat pump dryers reduce the extent of nonenzymatic browning reactions.

The color and aroma of herbs (e.g., parsley, rosemary, and sweet fennel) can be improved when compared with the commercial products. The sensory values were nearly doubled in the case of heat pump-dried herbs when compared with commercially dried products. There was no significant difference in the quality of herbs dried below a moisture content of 0.04 for the experimental drying temperatures (40°C–50°C) and relative humidity (0.30 and 0.40). A range of quality characteristics can be obtained by running the dryer within wide ranges of temperature and relative humidity. The use of modified atmospheres for drying sensitive materials such as food products is another important potential aspect of heat pump drying technology. During drying, oxygen-sensitive materials such as flavor compounds and fatty acids can undergo oxidation, giving rise to poor flavor, color, and rehydration properties. Using modified atmospheres to replace air will permit new dry products to be developed without oxidative reactions occurring [90].

18.3.3.3.2 Energy Efficiency

Removal of water in its liquid state rather than the vapor state allows the latent heat of vaporization to be captured, and only a small amount of sensible heat is lost with the condensate. The energy spent in drying is usually expressed as the "specific moisture-extraction rate" or SMER. The SMER for a well-designed heat pump dryer lies between 1 and 4 kg/kWh, whereas the SMER of a single-pass hot dryer is only 0.95 kg/kWh [90]. A general comparison of heat pumps with vacuum- and hot-air drying is presented in Table 18.2.

TABLE 18.2

General Comparison of Heat Pump Dryer with Vacuum and Hot-Air Drying

Parameter	Hot-Air Drying	Vacuum Drying	Heat Pump Drying
SMER (kg water/kWh)	0.12–1.28	0.72–1.2	1.0–4.0
Drying efficiency (%)	35–40	≤70	95
Operating temperature range (°C)	40–90	30–60	10–65
Operating % RH range	Variable	Low	10–65
Capital cost	Low	High	Moderate
Running cost	High	Very high	Low

18.3.3.3.3 Process Efficiency

Heat pump drying has the ability to operate at set conditions independent of outside ambient weather conditions. In addition, it is environment friendly, i.e., no gases or fumes are given off to the atmosphere. The condensate can be recovered and disposed of in an appropriate manner, and there is also the potential to recover valuable volatiles from the condensate [90]. Since drying takes place in a closed system, a low air-leakage rate allows for negligible heat loss.

Strommen [133] studied the drying of stockfish (unsalted) and klipfish (salted) in a heat pump dryer and found that the drying time was lowered by a factor of four with a high quality level. The klipfish was dried from 0.55 to 0.45 water content (wet basis) and the stockfish was dried from 0.80 to 0.20 water content. The inlet temperature and relative humidity in the tunnel were 20°C–25°C and 0.73, respectively. For heavily salted fish, at about 27°C burn spots were found. The above authors found the total energy consumption for oil burner airflow, and automatic control of humidity at the exhaust and heat pump to be 875, 479, and 125 kWh/t, respectively.

Increasing the humidity in the drying air slows down the drying process but improves the energy efficiency [18]. In general, heat pump drying efficiency and capacity are dependent on temperature and humidity. Also, the SMER increases with an increase in humidity in the dryer [90]. In a conventional air dryer, at low temperature (10°C–30°C), it is not possible to run the drying operation due to high ambient relative humidity (0.70–0.90), but heat pump drying can be performed at these low temperatures since the relative humidity can be lowered to 0.10.

The thermal insulation and gas tightness of the seals of the chamber structure is important in achieving high energy efficiency for the heat pump. In addition to the electrical energy required to drive the compressor, energy is also required to preheat the product and chamber structure, drive the fan for primary airflow over the product that is to be dried, and replace any heat loss through conduction and air leakages. Motors driving the fan and the compressor can be located within the chamber so that the residual heat produced by them is absorbed within the drying chamber instead of being lost to the atmosphere [90].

18.3.3.3.4 Progress and Applications

There are a number of technological problems to be overcome before the process can be applied to the food industry.

Capital cost: The capital cost of a heat pump dryer is higher than for a conventional hot-air dryer due to the requirement for an additional refrigeration system. However, its cost should be much less than that of vacuum or freeze drying.

Limited drying temperature: While low-temperature drying has a potential advantage, too low a temperature will limit the drying rate, which has implications for throughput. Also, slower drying rates at low temperature may give rise to potential microbial growth problems [90].

Process control and design: Like vacuum or freeze dryers, heat pump dryers are more amenable to batch drying because the drying takes place in a hermetically sealed container. The construction of a continuous drying process may require high engineering modeling and design costs. Therefore, the benefits need to be evaluated on the basis of cost rather than energy efficiency alone [90].

Microbiological safety: Most of the vegetative cells of microorganisms will be destroyed by normal hot-air drying at 60°C–80°C with only a few exceptions (e.g., heat-resistant bacteria, yeast, and molds) [37]. Although there are some concerns about the potential for the growth of microorganisms at the temperatures used in heat pump dryers, in practice there have been no reports of increased microorganisms in heat pump-dried foods compared to those dried by conventional means [18]. Serious microbiological problems may arise if the dryer is designed poorly. The problems of microbial growth should be the focus of further research.

18.3.3.4 Superheated Steam Drying

Superheated steam is used as a drying medium. The main advantages of this type of drying are that it can provide an oxygen-free medium for drying, and process steam available in the industry can be used without any capital cost. An oxygen-free medium has the potential to provide high-quality food products; however, it is important to generate more information regarding quality improvement and processing efficiency.

18.3.3.5 Impingement Drying

Impingement drying is an old technology that has only recently been applied to food products. An impingement dryer consists of a single gas jet (air or superheated steam) or an array of such jets, impinging normally on a surface. There are a great variety of nozzles that can be used, and selection of the nozzle geometry and multinozzle configuration have important relevance on the initial and operating costs, and product quality [80]. Some characteristics of impingement drying include rapid drying, popular for convection drying, and the large variety of nozzles available (multizones). Typically, the temperature and jet velocity in impingement drying may range from 100°C to 350°C and from 10 to 100 m/s, respectively [83].

18.3.3.6 Smoking

Smoking foods is one of the most ancient food preservation processes, and in some communities one of the most important. The use of wood smoke to preserve foods is nearly as old as open-air drying. Although not primarily used to reduce the moisture content of food, the heat associated with the generation of smoke also causes a drying effect. Smoking has been mainly used with meat and fish. The main purposes of smoking are it imparts desirable flavors and colors to the foods, and some of the compounds formed during smoking have a preservative effect (bactericidal and antioxidant) due to the presence of a number of compounds [25]. In many cases, smoking is considered as a pretreatment rather than a drying process. It was found that smoke is effective in preventing lipid oxidation in meat and fish products [152]. The level of fats affects texture, oiliness, and color of smoked salmon during storage [30,127].

Smoking is a slow process and it is not easy to control. Smoke contains phenolic compounds, acids, and carbonyls, and the smoky flavor is primarily due to the volatile phenolic compounds [30,57]. Wood smoke is extremely complex and more than 400 volatiles have been identified [44,77]. Polycyclic aromatic hydrocarbons are ubiquitous in the environment as pyrolysis products of organic matter. Their concentration in smoked food can reach levels hazardous for human health, especially when the smoking procedure is carried out under uncontrolled conditions [81]. Wood smoke contains nitrogen oxides, polycyclic aromatic hydrocarbons, phenolic compounds, furans, carbonylic compounds, aliphatic carboxylic acids, tar compounds, carbohydrates, pyrocatechol, pyrogallols, organic acids, bases, and also carcinogenic compounds like 3:4 benzpyrene. Nitrogen oxides are responsible for the characteristic color of smoked foods, whereas polycyclic aromatic hydrocarbon components and phenolic compounds contribute to its unique taste. These three chemicals are also most controversial from a health perspective [77].

It is important to scrutinize processing conditions, which must be standardized, controlled, monitored, and documented so that the potential for producing toxic, or even lethal, food products is eliminated. This is especially true for seafood products, which may contain food-poisoning organisms of marine origin that are more difficult to control than those from land sources [51]. Color development in smoked fish is a complex process. Maillard type with glycolic aldehyde and methyglyoxal in the dispense phase of smoke is dominant role in developing golden color. Several types of synthetic colors, paprika, caramel, and seasoning can also be used [2].

All smoked fish must be stored chilled or vacuum packed to prolong shelf life. Brining and smoking affects on sensory quality as well as microbial preservation. Hansen and Huss [47] identified the microflora on spoiled, sliced, and vacuum-packed cold-smoked salmon from three different sources. Lactic acid bacteria dominated the microflora; in some cases large numbers of *Enterobacteriaceae* were also present. The microflora on cold-smoked salmon appeared to be related to the source of contamination, i.e., the raw material or the smokehouse rather than being specific for the product.

The traditional method of smoking fish involves passing hot smoke, from a range of woods, over the fish to partially dry it and impart the flavor and aroma of the smoke. Disadvantages of this method include a lack of control over the process and the finished product, with consequent health concerns if the surface of the fish is not properly dried. The smoking process involves extensive handling of raw and finished products. Smoked food is prepared with either of two basic procedures. One cooks the product (hot smoking) and the other does not (cold smoking). Cold smoking devices have one basic function—to apply smoke to the product. Hot smoking devices have the added function of applying heat. The hot-smoke process for smoking fish differs from the cold-smoke process in a fundamental way. The cold-smoke process requires that the fish reach an internal cooking temperature below 35°C, while the hot-smoke process cooks the fish to the center at a minimum of 62.8°C for at least 30 minutes. Also, both processes should ensure at least 3.5% salts in water-phase of fish muscle. Between these two extremes are the temperatures that can create an environment favorable to the growth of food-poisoning bacteria. As an additional safety margin, hot-smoked fish should always be cooled to less than 3.3°C immediately after smoking and held at that temperature until consumed to prevent the growth of food-poisoning bacteria. Both hot- and cold-smoked fish are preserved primarily by controlling the salt and moisture content (water-phase salt). Smoke deposition is effective only in controlling surface spoilage [51].

The hot smoking of fish requires five steps, each with different goals and operating conditions. These steps are surface drying, smoking, drying, heating/cooking, and cooling. Surface drying is the removal of surface moisture, leaving a protein coating (pellicle) on each piece of fish so that it accepts an even smoke deposit. The second step involves producing a dense atmosphere of smoke and conditions where smoke is deposited evenly on the surface of each piece to insure good flavor, color, and surface preservation. Often, color does not develop until after the surface of the fish reaches 54.4°C–60°C during the cooking step. The next step involves evenly drying the fish to reduce moisture, raise the water-phase salt, and establish final texture. This is a critical step in producing safe products—heating each piece of fish to at least 62.8°C and holding that temperature for at least 30 minutes. This is followed by cooling the fish to below the cooking temperature (48.9°C–60°C) in the smokehouse as quickly as possible. A suitable sanitary refrigerated room is usually more practical and cost-effective than a refrigerated smokehouse. Cold-smoke procedures do not use step 4, i.e., heating/cooking. Usually these five cycles require 8–12 h. Cycles of 4 h or less are possible with thin and lightly smoked products [51]. The differences in the process employed depend primarily upon the type of fish and regional preferences for a particular product. Different schedules for different fish species are specified [30]. A smokehouse is equipped with a smoke generator where smoke is passed over water to remove tar and solid particles. Good manufacturing practice (GMP) from the FDA sets the minimum standards for time/ temperature smoking cycles, salt and moisture content, manufacturing, holding and shipping temperatures, process monitoring and record keeping, and packaging.

More modern methods of smoking fish use formulations of liquid smoke to provide flavor and a range of methods of drying to reduce water activity on the surface. The fish is dipped in smoke solutions prior to drying. Most drying methods use heat to change the relative humidity of the air passing over the fish. This is an inefficient way of using energy, and in addition the heat drives off many of the aromatic chemicals that go to make up the aroma, flavor, and color of the product. This can be overcome by using an energy-efficient heat pump dryer, where drying is performed in a closed chamber. *Smoke solutions* are available, either being condensed products from the dry distillation of wood or synthetically prepared mixtures of phenols. The use of smoke condensates offers some advantages. They are easy to apply and their concentration can be controlled. They can be analyzed, purified if necessary, and their antimicrobial activity can be evaluated. Sunen [136] identified the minimum inhibitory concentration of smokewood extracts against spoilage and pathogenic microorganisms associated with food. They found that the effectiveness in inhibition varied with the type of commercial liquid smoke. Synthetic smokes are nearer to actual smoke curing and harmful components can be eliminated from synthetic smokes. The odor, composition of flavor compounds, and antimicrobial activity of the smoke are recognized to be highly dependent on the nature of wood. Some studies have recognized beech and oak woods as those which produce wood smoke with the best sensory properties [43]. Further, herbs, spices (bay leaves, black peppers, cloves, coriander seed, and spice), or pinecones may also be added to produce unique aromatic smoke flavors [57]. Bacteriocin treatment was found effective in inhibiting *Listeria monocytogenes* on salmon packaged under vacuum or modified atmosphere [137].

18.3.4 Modified Atmosphere Drying

This is a new concept of drying foods using heat pump dryers, which uses modified atmospheres such as nitrogen and carbon dioxide, for better quality and preservation of constituents of foods, prone to oxidation. Technologies to create the modified atmosphere drying are now evolving. O'Neill et al. [85] showed that the browning of apple cubes during drying could be arrested if the oxygen level in the atmosphere is less than 0.5%. Apple cubes dried in nitrogen atmosphere gave more open pores and uniform shrinkage than those dried in air and vacuum. Rahman et al. [108] studied the microbial (aerobic plate count, *Pseudomonas*, *Staphylococcus*, molds) and physicochemical (pH, expressed juice, fatty acid profile, rehydration ratio, color) characteristics of sun, air, vacuum, freeze, and modified atmosphere (nitrogen gas) dried goat meat. The modified atmosphere drying showed significant improvement in selected quality attributes such as shrinkage, color, types of molds, and peroxide values (PV).

Modified atmosphere heat pump dehumidifier (MAHPD) drying is a relatively new development described by Perera [91,92] and Hawlader et al. [49,50]. The fact that heat pump dehumidifier (HPD) drying is conducted in an enclosed, insulated chamber is made use of in the development of the MAHPD drying system. The air in the dehumidifier chamber is replaced with an inert atmosphere such as nitrogen, carbon dioxide, or their mixtures. Replacement of the air inside the chamber is easily carried out by exhausting the chamber using a vacuum pump and then breaking the vacuum using an inert gas. Vacuum exhaustion is a more cost-effective way to replace air than by direct purging with the specific inert gas. Replacement of air with carbon dioxide or nitrogen by purging requires over 50 volumes to achieve an oxygen level of less than 0.5%. Schematic diagram of the MAHPD drying system is shown in Figure 18.5. This consists of a sealed drying vessel connected to the heat exchanger unit. The drying vessel has provision for introduction of nitrogen or for evacuation through a valve connection. The MAHPD system shown also has provisions for introducing microwave energy for heating the product, through a slotted waveguide running down the wall of the chamber parallel to the axis of the chamber. A PLC control panel connected to a remote PC and monitor controls the whole system. The product is carried on microwave-transparent plastic trays stacked vertically on a rotating platform, which is mounted on a load cell, so that weight loss can be monitored and recorded on the PC. The current prototype is essentially a batch process, but it can be semiautomated depending on the products and pretreatments required for specific products. Some of the pretreatments may include vacuum infusion or osmotic dehydration before MAHPD drying. After the product is loaded on to the trays and stacked on the platform, the drying chamber is evacuated to 600–700 Pa for 30 minutes, after which, the vacuum is

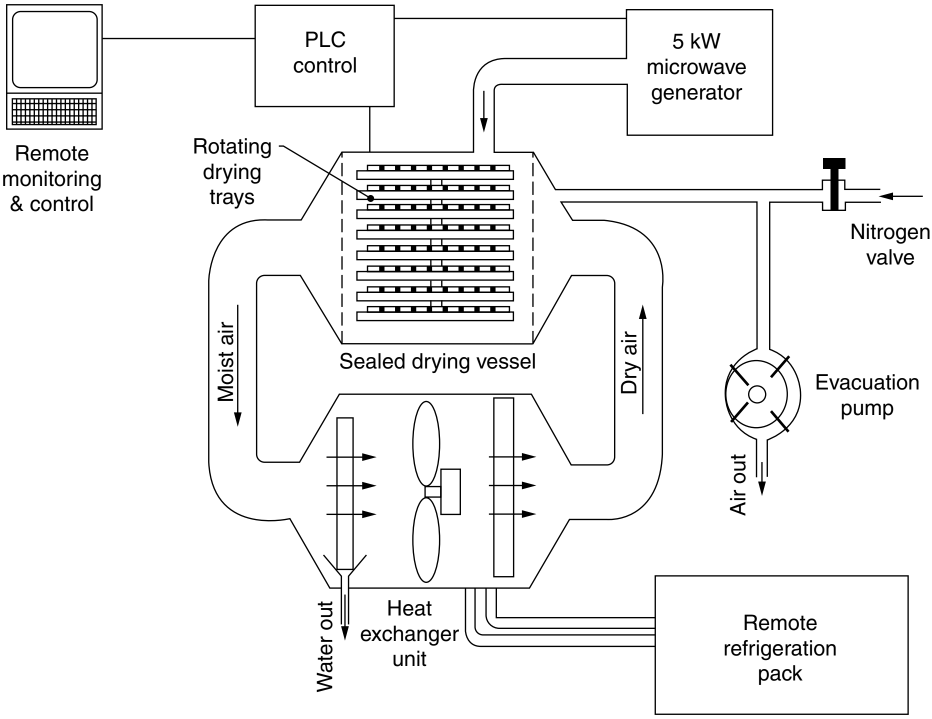

FIGURE 18.5 Schematic diagram of the MAHPD drying system. (From Perera, C. O. 2001. Proceedings of the 2nd Asian-Oceania Drying Conference. Penang, Malaysia, 2001; Perera, C. O. 2004. In: *Dehydration of Products of Biological Origin, Chapter 6.* Science Publishers Inc., Enfield, NH, USA. pp. 153–163.)

broken with the selected modified atmosphere and normal HPD drying is carried out in this modified atmosphere. Microwave energy improves the drying rate. The surface temperature of the product is monitored using an infrared detector. Controls can be set for the microwave energy to cut off at a preset surface temperature of the product, so that overheating can be minimized.

The quality of apple cubes dried by MAHPD was evaluated using several techniques. The color of these cubes was measured by Hunter Lab spectrophotometer. Density and porosity of the fruit tissues were measured by helium gas pycnometer and structural properties of the fruit tissues were evaluated by scanning electron microscopy [50]. It was found that apple tissues dried by MAHPD had lighter color, lower bulk density values, porous (noncollapsed) structure, and better rehydration properties compared with those dried by most other common drying methods. Hawlader et al. [50] also found that fruits dried by MAHPD retained the highest level of nutrients, such as vitamin C, and flavor compounds [50]. These observations suggest that MAHPD is highly suited for drying sensitive food and pharmaceutical products.

18.4 Pretreatments

18.4.1 Blanching

Pretreatments are common in most of the drying processes in order to improve product quality, storage stability, and process efficiency. In recent years, an improvement in quality retention of the dried products by altering processing strategy and pretreatment has gained much attention. Blanching is a process of preheating the product by immersion in water or steam. The main purpose of blanching is to inactivate the naturally occurring enzymes present in foods, since enzymes are responsible for off-flavor development, discoloration or browning, deterioration of nutritional quality, and textural changes in food materials. Other advantages are that it removes air-bubbles from vegetable surfaces and from intercellular spaces, reduces the initial microbial load, cleans raw food materials initially, facilitating preliminary operations such as peeling and dicing, and improving color, texture and flavor under optimum conditions [13,36,73]. Blanching may have disadvantages, for example, it may change the texture, color, and flavor because of the heating process [45,125]; it increases the loss of soluble solids, such as vitamins [5,14], especially in the case of water blanching; it may change the chemical and physical states of the nutrients and vitamins [1,13,33]; and it has adverse environmental impacts, such as large water and energy usage, and problems of effluent disposal.

Time and temperature of blanching are the important factors for achieving optimum quality of the dried product [56]. The normal blanching temperature varies from 80°C to 100°C. Recently, low-temperature and long-time blanching has been proposed for better texture and retention of some nutrition components [78,100]. The temperature used is between 50°C and 70°C. Blanching times correlated with the flavor and sensory attributes of dried fruits and vegetables [125]. Limiting blanching time, rapid cooling, and alternative blanching methods and combinations may result in dried products with better flavor. Processing methods that include steam and microwave blanching, and nonthermal enzyme inactivation such as high pressure and ohmic heating may hold out potential for future blanching processes, with less detrimental effects on flavor while maintaining optimum texture.

18.4.2 Sulfur Dioxide Treatment

Sulfur dioxide preserves the texture, flavor, vitamin content, and color that make food attractive to the consumer. Sulfur dioxide treatment is used widely in the food industry to reduce the fruit-darkening rate during drying and storage, and preserves ascorbic acid and carotene. Sulfur dioxide taken up by the foods displaces air from the tissue in plant materials, softens cell walls so that drying occurs more easily, destroys enzymes that cause darkening of cut surfaces, shows fungicidal and insecticidal properties, and enhances the bright attractive color of dried fruits [131]. Permitted levels of sulfur dioxide and other additives (solutes) in dried foods vary from country to country. According to the Institute of Food Technologists (IFT) [54] expert panel, sulfur dioxide in dried fruits is set at the highest level by food legislation. The allowed limit is 2000 mg/kg of dried fruit. Sulfiting treatment can be done by burning sulfur or soaking foods in sulfite solution. Gaseous sulfur dioxide can be produced by burning sulfur with oxygen in the air and then circulating it to the smoking chamber. Potential advantages in using a bisulfite solution are [131] decreased air pollution, better control of the sulfuring process, greatly shortened sulfuring time, and decreased desorption losses during drying.

The chemical reactions of sulfur dioxide when it is added to fruits and other food products are complex [15]. Sulfite could be bound or free in the food matrix. The bound sulfite is considered to have no retarding effect on product deterioration; thus, it is important to know the factors that influence binding [15]. The amount of bound sulfite depends on pH; carbonyl groups of aldehydes, acetaldehyde, pyruvic acid; and the availability of oxygen, sugars, and starch [15,19,89]. Sulfiting and blanching can also be used together for pretreatment [139]. Sulfiting ruptures and collapses cells, resulting in a smaller cell volume and hardness of the dried samples [82,97]. A number of factors affect sulfur dioxide uptake by fruits and vegetables, including concentration and temperature of dipping solution, time of dipping, geometry and conditions of sample (i.e., peeled or unpeeled, whole or sliced), and agitation of solution [114,131].

18.4.3 Salting or Curing

Salting or curing is a natural type of osmotic dehydration. Curing was originally developed to preserve certain foods by the addition of sodium chloride. In the food industry, the application of curing is related only to certain meat, fish, and cheese products. Today sodium chloride, and sodium and potassium nitrite (or nitrate) are considered as curing salts. Salting is one of the most common pretreatments used for fish products. It converts fresh fish into shelf-stable products by reducing the moisture content and acting as a preservative. In combination with drying, these processes contribute to the development of characteristic sensory qualities in the products, which influence their utilization as food [124]. Although curing was originally a mechanism for preservation by salting, over several millennia additional processes concomitant with curing have evolved, notably fermentation, smoking, drying, and heating. Curing may have different connotations: in meat, salt and nitrite or nitrate are always added; in fish, salt is always added, but nitrite only rarely; and in cheese, which always contains salt but infrequently contains nitrate, the term curing is applied to the production of desirable proteolytic and lipolytic changes. In the past half-century, cured products have been developed that are not stable unless refrigerated. Indeed, most cured meat products must be refrigerated to remain safe and wholesome, and during the past two decades even the packaging of many classes of cured products has become important in extending the period during which the product remains wholesome [128]. Cured meats can be divided broadly into three groups: unheated, mildly heated (pasteurized to a center temperature of 65°C–75°C), and severely heated (shelf stable after heating to 100°C–120°C) [128].

In addition to the curing salts and related processes mentioned above, additives collectively known as adjuncts are used in many cured meat products. These include ascorbates, phosphates, glucono-d-lactone, and sugars. Adjuncts are used primarily to obtain or maintain desirable changes, the ascorbates in connection with color and the others in connection with pH, texture, and in some cases flavor. Adjuncts may also affect safety. The concentration of each curing agent depends on the nature of the food products and the technology used in individual countries [128].

18.4.4 Other Dipping Pretreatments

Dipping treatment with chemicals is also used in addition to blanching or sulfite treatment. The dipping treatment is a process of immersion of foods in a solution containing additives. Usually, the concentration level is below 5% and the dipping time below 5 minutes, whereas osmotic dehydration is carried out at higher concentrations and for long processing times. The main purpose of the dipping treatment is to improve the drying characteristics and quality. Certain chemicals are used to enhance the rate of dehydration [45]. Among these compounds, methyl and ethyl oleate, or olive oil are the most common [16,93,95,148]. Methyl oleate has realized the greatest usage because of economics and its higher taste threshold. A carbonate-oleate combination was found to be superior when used alone in accelerating drying rate [109,112,140]. A synergistic effect results from the combined use of alkali

TABLE 18.3

Chemicals Used for Dipping Treatment

Type	Compounds
Chemicals	
Esters	Methyl oleate, ethyl oleate, butyl oleate
Salts	Potassium carbonate, sodium carbonate, sodium chloride, potassium sorbate, sodium polymetaphosphate
Organic acids	Oleic acid, steric acid, caprillic acid, tartaric acid, oleanolic acid
Oils	Olive oil
Alkali	Sodium hydroxide
Wetting agents	Pectin, tween, nacconol
Others	Sugar, liquid pectin
Surfactants	
Nonionic	Monoglycerides, diglycerides, alkylated aryl polyester alcohol, polyoxyethylene sorbitan monostearate, sorbitan monostearate, D-sorbitol, polyoxyethylene
Anionic	Sodium oleate, steric acid, sorbitan heptadecanyl sulfate, dimethyl-benzyl-octyl ammoniumchloride

carbonates and methyl oleate for drying. When excess carbonate was used, drying was further accelerated. Sodium carbonate was less effective than potassium carbonate; however, the cost of sodium salt is about a fifth of that for potassium.

Esters affect the waxy surface of fruits by altering the physical arrangement of the surface wax platelets, thus allowing moisture to more readily evaporate from the fruit. This was confirmed using electron microscopy for grapes and sweet cherries [48]. Increase of the hydrophilic groups on the wax surface by a reversible attachment of long-chain fatty acids and their esters was observed. The increase in hydrophilic groups on the normally lipophilic wax surface would form a sequence of attachment sites to facilitate the transfer of water through the crystalline wax layer [21,41]. The addition of potassium carbonate is necessary, possibly acting by saponification of fatty acids such as oleic, steric, and oleanolic acids, which are known constituents of grape wax. Table 18.3 shows the chemicals used for dipping treatment.

18.4.5 Freezing Pretreatment

Freezing treatment affects the drying process. The rehydration rate of air- and vacuum-dried fruits and vegetables subjected to freezing treatment increased to a level comparable with that of freeze-dried products [63]. It was also noticed that the longer the duration of freezing, the better the rehydration kinetics of dried products. This was due to the formation of large ice crystals by slow freezing. Drying rate was not dependent on the pressure in the drying chamber—ranging between 20 and 50 mm Hg, and above 50 mm Hg the drying rate decreased rapidly with pressure.

18.4.6 Cooking

Cooking at different pressure levels before drying can destroy microorganisms and affect the physicochemical properties of dried products. The bacterial load on the final product can thus be reduced considerably, and the cooked product can be minced and spread evenly on drying trays with much less trouble than the raw material. Precooking is usually used for rice, beef [6], fish, and beans [29]. Formation of superficial pellicle (case-hardening) may be avoided by precooking, which considerably retards drying. It is clear that the more severe the initial conditions of cooking, the more stable is the subsequently dehydrated product. When an animal or plant is killed, its cells become more permeable to moisture, as pointed out by Potter [96]. When the tissue is blanched or cooked, the cells may become still more permeable to moisture. Generally, cooked vegetable, meat, or fish is dried more easily than their fresh counterparts, provided that the cooking does not cause excessive shrinkage or toughening [96]. Cooking also results in a decrease in water-holding capacity of meat products [132].

18.5 Quality Changes During Drying

18.5.1 Selection of Variety

Optimum freshness plays an important role in determining the quality and stability of dried foods; fresher the raw material, more stable and better is the quality of the product. Suitable varieties of produce with the desired maturity should be used to achieve a product that is best in quality [135]. The quality characteristics of dried foods can be grouped as microbial, chemical, physical, and nutritional (Table 18.4).

18.5.2 Microflora in Dried Foods

Multiplication of microorganisms should not occur in properly processed dehydrated foods, but they are not immune to other types of food spoilage. If dried foods are safe in terms of pathogenic microbial count and toxic or chemical compounds, then acceptance depends on the flavor or aroma, color, appetizing appearance, texture, taste, and nutritional value of the product. Microbial standards are usually based on the total number of indicator organisms or number of pathogens [111]. The microbial load and its changes during drying and storage are important for establishing a standard that will ensure food safety. Poor processing, handling, and storage practices often result in a limited storage life of dried fish [150]. Perishable foods such as meat and fish are prone to rapid microbial spoilage; thus, adequate care must be taken in drying. The microbial load for dried mackerel ranged from 3×10^3 colonies per gram sample to too numerous to count. No evidence of spoilage was detected even when the samples had water activity from 0.72 to 0.74. The isolates found were *Alcaligenes*, *Bacillus*, *Leuconostoc*, *Micrococcus*, *Halobacterium*, *Flavobacterium*, *Halococcus*, *Aspergillus*, and *Penicillium.* All the samples were positive for *Coliform, Streptococcus,* and *Staphylococcus*. *Vibrio* and *Clostridium* were not detected while *Salmonella* was detected only in some samples [111]. Brining and drying decreased the microbial load but did not eliminate the pathogens. Wheeler et al. [150] studied the common fungi involved in spoiling dried salted fish. They studied the mycoflora of dried salted fish with emphasis on visible spoiled fish and spoilage fungi. A total of 364 isolates from 74 fish were cultured and identified. Wheeler and Hocking [149] studied the effect of water activity and storage temperature on the growth of fungi associated with dried salted fish. Microorganisms did grow during the drying of highly perishable products such as fish (Trevally) in heat pump dehumidifier drying at low temperatures of 20°C–40°C. Lower temperatures gave lower counts regardless of the relative humidity of drying. Sulfur-producing organisms formed a significant portion of the total flora of dried fish. Rahman et al. [106] studied the endogenic microflora changes in tuna mince during convection air drying between 40°C and 100°C. A drying temperature of 50°C or below showed no lethal effect on the microflora, but instead aided growth. The drying temperature of fish must be above 60°C to avoid microbial risk in the product. The actual optimum temperature above 60°C should be determined based on other quality characteristics of the dried fish [106].

Reducing the water activity of a product inhibits microbial growth but does not result in a sterile product. The highest possible drying temperatures should be used to maximize thermal death even though low drying

TABLE 18.4

Quality Characteristics of Dried Foods

Microbial	Chemical	Physical	Nutritional
Pathogens Spoiling Toxin	Browning Oxidation Color loss Aroma development Removal of undesired components	Rehydration Solubility Texture Aroma loss Porosity Shrinkage Pores' characteristics Crust formation Structure	Vitamin loss Protein loss Functionality loss Fatty acid loss

temperatures are best for maintaining organoleptic characteristics [86]. Another alternative is to use high drying temperatures initially at high moisture content and then drying at a low temperature. The microbial deactivation kinetics depends on several factors such as variety, water content (i.e., water activity), temperature, and compositions of the medium (acidity, types of solids, pH, etc.) as well as on the heating method [71,58,121]. Models to predict the decimal reduction time (D-value) were also developed as a function of temperature, pH, and water activity for isothermal conditions [20,38]. These models could not be used in the case of drying conditions since the level of water content does not remain the same for each temperature studied. Bayrock and Ingledew [11] measured the D-values for changing moisture content (i.e., drying) and moist conditions (i.e., no change of moisture during heating). The heat resistance of the microorganism increased significantly during drying compared with the moist heat conditions. During drying of tuna, Rahman et al. [106] found that the D-value for endogenous microflora varied from 12.66 to 2.64 h when drying temperature varied from 60°C to 100°C, respectively. As expected, the values decreased with the increase in temperature, which indicates that an increase in drying temperature increased the lethal effect. However, the D-values at 100°C were much lower than at 90°C or below. This may be due to the high drying rate at 100°C [10,106]. Rahman et al. [105] investigated the changes of endogenous bacterial counts in minced tuna during dry heating (convection air drying) and moist heating (heating in a closed chamber) as a function of temperature. The D-values for total viable counts decreased from 2.52 to 0.26 h for moist heating and from 2.57 to 0.34 h for dry heating, respectively, when temperature was maintained at a constant of within 60°C–140°C. In both cases, increasing temperature caused significant decrease in D-values, whereas the effect of the heating methods was not significant. The Z-values were found to be 144°C and 46°C for temperatures between 60°C–100°C and 100°C–140°C, respectively. Rahman et al. [105] also identified the types and characteristics of endogenous microbes present in fresh and dried tuna. Initially, tuna contained a mixture of different microbes, of which some are more heat- and osmotolerant than others. In dried tuna, the predominant microbes were moderately osmotolerant and the dominant microbes were sensitive to heat.

18.5.3 Browning Reactions

Browning reactions change color, decrease nutritional value and solubility, create off-flavors, and induce textural changes. Browning reactions can be classified as enzymatic or nonenzymatic, with the latter being more serious as far as the drying process is concerned. The two major types of nonenzymatic browning are caramelization and Maillard browning. In addition to moisture level, temperature, pH, and composition are the other parameters that affect the rate of nonenzymatic browning. The rate of browning is most rapid in the intermediate moisture range and decreases at very low and very high moistures. Browning tends to occur primarily at the center of the drying period. This may be due to the migration of soluble constituents toward the center. Browning is also more severe near the end of the drying period, when the moisture level of the sample is low and less evaporative cooling is taking place that causes the product temperature to rise. Several suggestions were found to help reduce browning during drying. In all the cases, it was emphasized that the product should not experience unnecessary heat when it is in its critical moisture content range [86].

Maillard-type nonenzymatic browning reactions in processed meat products also contribute to the product's external surface color. The main browning reaction involves the reaction of carbonyl compounds with amino groups, although lesser amounts of carbonyl browning also occur. Muscle usually contains small amounts of carbohydrates in the form of glycogen, reducing sugars, and nucleotides, while the amino groups are readily available from the muscle proteins. Browning occurs at temperatures of 80°C–90°C and increases with time and temperature [22]. A loss of both amino acids and sugars from the tissue occurs as a result of the browning reaction. Lysine, hystidine, threonine, methionine, and cysteine are some of the amino acids that may become involved in browning [52]. Potter [96] identified that Maillard browning proceeds most rapidly during drying if the moisture content is decreased to a range of 15%–20%. As the moisture content drops further, the reaction rate slows down, and therefore products dried below 2% moisture further color change are not perceptible even during subsequent storage. Drying systems or heating schedules generally are designed to dehydrate rapidly through the 15%–20% moisture range so as to minimize the time for Maillard browning. In carbohydrate foods, browning can be controlled by removing or avoiding amines and in protein foods by eliminating the reducing sugars.

18.5.4 Lipid Oxidation

Dehydrated foods containing fats are prone to develop rancidity after a period, particularly if the water content is reduced too much. Fish oils or fats are more unsaturated than beef or butter, and they are usually classified as drying oils because they contain considerable proportions of highly unsaturated acids. The behavior of drying oils toward atmospheric oxygen is well known, and oxidation is a serious problem for commercial drying of fatty fish and seafood. The flesh of some fatty fish, such as herrings, contains a fat pro-oxidant that is not wholly inactivated by heat [9].

Lipid oxidation is responsible for rancidity, development of off-flavors, and the loss of fat-soluble vitamins and pigments in many foods, especially in dehydrated foods. Factors that affect oxidation rate include moisture content, type of substrate (fatty acid), extent of reaction, oxygen content, temperature, presence of metals and natural antioxidants, enzyme activity, UV light, protein content, free amino acid content, and other chemical reactions. Moisture content plays a big part in the rate of oxidation. At water activities around the monolayer ($a_w \approx 0.3$), resistance to oxidation is greatest.

The elimination of oxygen from foods can reduce oxidation, but the oxygen concentration must be very low. The effect of oxygen on lipid oxidation is also closely related to the product porosity. Freeze-dried foods are more susceptible to oxygen because of their high porosity. Air-dried foods tend to have less surface area and pores due to shrinkage, and thus are not affected by oxygen. Minimizing oxygen level during processing and storage, and the addition of antioxidants as well as sequesterants were recommended in literature to prevent lipid oxidation [86]. Fish oils or fats are drying oils, which rapidly absorb oxygen from the air and harden just as paints harden on exposure to air. Fatty fish must be dehydrated quickly in a vacuum and must be stored in vacuum or in an inert gas atmosphere [57].

Antioxidants directly added to herrings before air drying are ineffective, but antioxidants released from wood smoke (used in air drying), which contains some of the simple antioxygenic phenols, stabilizes the fat of the dehydrated products considerably [9]. Oxidation of the fat normally occurs during dehydration. Herrings and haddock dried at 80°C–90°C compared to a lower temperature were found to be more stable during storage [9]. One factor could be the formation of browning products from protein nonfatty part, which gave antioxidant activity. The effectiveness of nonenzymatic browning products in preventing lipid oxidation was demonstrated and is one of the mechanisms hypothesized by Karel [59] to prevent lipid oxidation.

The effects of water on the destruction of the protective food structure in some specific dehydrated foods are probably involved in the prevention of lipid oxidation in heated meat systems [59]. In systems containing both surface lipids and lipids encapsulated within a carbohydrate, polysaccharide, or protein matrix, the surface lipids oxidize readily when exposed to air. The encapsulated lipids, however, do not oxidize until the structure of the encapsulated matrix is modified and destroyed by the adsorption of water [129]. Another reason is the increase of oxygen diffusion by increasing molecular mobility above the glass–rubber transition [113].

The peroxide values of different dried meat samples were studied by Rahman et al. [108]. The values were significantly different according to the methods of drying. Freeze drying gave the highest value, while air drying gave the lowest value. Similar results were also observed in the case of air-dried, vacuum-dried, and freeze-dried tuna meat [104]. Rahman et al. [104] indicated that this was due to the fact of increased oxygen diffusion and higher exposed surface area in case of freeze-dried samples, which was created by high porosity (volume faction of void or air in the sample).

18.5.5 Changes in Proteins

The protein matrix in muscle has a marked effect upon its functionality and properties [122]. The nonfatty part of fish is very susceptible to changes caused by the high temperature of initial cooking, as well as drying and storage. Every process involved in the conversion of muscle to meat alters the characteristics of the structural elements [132]. Heating is believed to cause the denaturation of the muscle proteins even below 60°C but not enough to greatly shear resistance [123]. The decrease in shear observed at 60°C was attributed to collagen shrinkage. Hardening at 70°C–75°C was believed to be due to increased cross-linking and water loss by the myofibrillar proteins, while decreasing shear at higher temperatures may indicate solubilization of collagen [22]. After 1 h at 50°C, the collagen fibrils of the endomysium appear beaded, which is brought about by their close association with the heat-denatured noncollagenous proteins in the extracellular spaces. Heat denaturation of the lipoprotein plasmalemma results at a temperature of 60°C after 1 h. The breakdown products of the plasmalemma are large granules and are often associated with the basement lamina, which appears to survive intact even after heating at 100°C for 1 h [115,116].

18.5.6 Structural Changes

Structural changes in food during drying are usually studied by microscopy. Microscopy provides a good tool to study this type of phenomenon as well as other types of physical and chemical changes during the drying of food materials. Shrinkage occurs first at the surface and then gradually moves to the bottom as the drying time [147] increases. The cell walls became elongated. As drying proceeds at high temperature, cracks are formed in the inner structure. Using microscopy, it was found that the shrinkage of apple samples dried by convection is significantly anisotropic while less damage to the cell structure during freeze drying leads to a more isotropic deformation [79]. The cellular structure of microwave-vacuum-dried apple with and without osmotic treatment indicated collapse of the cellular structure in the untreated apple [35]. Osmotic treatment prior to vacuum drying preserved the cellular structure by keeping intact their three-dimensional nature. Electron microscopic investigations of the cell structure in dried carrots and green beans showed that drying leads to shrinkage and twisting of the cells and clumping of the cytoplasm [42]. Histological changes in air-dried, freeze-dried, and osmotically treated freeze-dried samples showed that air-dried samples exhibited the elongated and thinned cell wall and enlarged intercellular air spaces [67].

Heating produces major changes in muscle structure. Voyle [145] reviewed modifications in cooked tissue observable with the scanning electron microscope. Alterations in muscle structure due to heating include coagulation of the perimysial and endomysial connective tissue, sarcomere shortening, myofibrillar fragmentation, and coagulation of sarcoplasmic proteins [53,145]. Heating and drying intensifies the detachment of the myofibrils from the muscle fiber bundles, which is caused mainly by electrical stunning or stimulation and improper conditioning following slaughter [24].

Rehydration is maximized when cellular and structural disruption such as shrinkage is minimized [86]. Chang et al. [23] illustrates the morphological changes that occur in the appearance of muscle fiber bundles during cooking and drying in a convection-heated rotary dryer. They found that after cooking, the fibers are bound together in a compact bundle. The bundle size is gradually reduced due to the effects of heating and tumbling during the early stage of predrying in the modified clothes dryer. Apparently, the bundle size is expanded with the endomysial capillary moisture being removed during drying.

18.5.7 Case Hardening or Crust Formation

During drying, the concentration of moisture in the outer layers of foods is less than in the interior, since the outer layers necessarily lose moisture before the interior. This surface shrinkage causes checking, cracking, and warping. This type of shrinkage causes moisture gradient and resistance near the surface. In extreme cases, shrinkage and drop in diffusivity may combine to yield a skin practically impervious to moisture, which encloses the volume of the material so that the interior moisture cannot be removed. This is called case hardening. In food processing, case hardening is also commonly known as crust formation. The extent of crust formation can be reduced by maintaining flattening moisture gradients in the solid, which is a function of drying rate. The faster the drying rate, the thinner the crust [3]. Crust (or shell) formation may be either desirable or undesirable in dried food products. In microencapsulation of flavors, rapid crust formation is required to prevent flavor losses. Achanta and Okos [3] pointed that crust formation may be inhibited by allowing the drying rate to be slow enough that moisture loss from the product surface is replenished by moisture from the inside. Crust formation is also important in explosion puffing. In this case, the high-moisture product is exposed to rapid drying conditions such as high temperature and vacuum, which create a crust. The impermeable crust, coupled with the extreme drying conditions, results in rapid moisture vaporization and causes large internal pressures to build up, resulting in product expansion/puffing. During the expansion stage, stress buildup in the glassy surface may cause the surface to crack, allowing vapor to escape.

18.5.8 Shrinkage or Collapse and Pore Formation

Two types of shrinkage are usually observed in the case of food materials—isotropic and anisotropic shrinkage. Isotropic shrinkage can be described as the uniform shrinkage in all geometric dimensions of the materials. Anisotropic shrinkage is described as the nonuniform shrinkage in the different geometric dimensions. In many cases, it is important to estimate the changes in all the characteristic geometric dimensions to characterize a material. In the case of muscle, such as in fish and seafood, shrinkage in the direction parallel to the muscle fibers was significantly different from that perpendicular to the fibers during air drying [8,103]. This is different from the isotropic shrinkage of most fruits and vegetables.

Shrinkage is an important phenomenon impacting dried food product quality by reducing product wettability, changing product texture, and decreasing product absorbency. Depending on the end use, crust and pore formation may be desirable or undesirable. If a long bowl life is required for a cereal product, a crust product that prevents moisture reabsorption may be preferred. If a product (such as dried vegetables in instant noodles) with good rehydration capacity is required, high porosity with no crust is required. Rahman [102] provides the latest on the mechanism of pore formation in foods during drying and related processes. Glass transition theory is one of the proposed concepts to explain the process of shrinkage and collapse during drying and other related processes. According to this concept, there is negligible collapse (more pores) in the material if processed below glass transition and higher the difference between the process temperature and the glass transition temperature, the higher the collapse. The methods of freeze drying and hot-air drying can be compared based on this theory. In freeze drying, since the temperature of drying is below T_g' (maximally freeze concentrated glass transition temperature), the material is in the glassy state. Hence shrinkage is negligible. As a result, the final product is very porous. In hot-air drying, since the temperature of drying is above T_g' *or* T_g, the material is in the rubbery state and substantial shrinkage occurs. Hence, the food produced from hot-air drying is dense and shriveled [3]. However, the glass transition theory does not hold good for all products. Other concepts such as surface tension, structure, environment pressure, and mechanisms of moisture transport also play important roles in explaining the formation of pores. Rahman [102] hypothesized that as capillary force is the main force responsible for collapse, so counterbalancing of this force causes formation of pores and lowers shrinkage. The counterbalancing forces are due to the generation of internal pressure, variation in moisture transport mechanism, and environmental pressure. Other factors could be the strength of the solid matrix (i.e., ice formation, case hardening, and matrix reinforcement).

18.5.9 Stress Development and Cracking or Breakage

During air drying, stresses are formed due to nonuniform shrinkage resulting from nonuniform moisture and temperature distributions. This may lead to stress crack formation when stresses exceed a critical level. Crack formation is a complex process influenced interactively by heat and moisture transfer, physical properties, and operational conditions [70]. The relative humidity of air and temperature are the most influential parameters that need to be controlled to eliminate the formation of cracks.

Checking and breakage of dried foods has two undesirable consequences—loss of valuable product and loss of consumer satisfaction [3]. Cracking is detrimental to grain quality since the affected kernels are more susceptible to mold attack during storage and pathogenic invasion after seeding. Cracked grains are also of lower organoleptic quality, which limits their use in direct food preparation. Internal cracking in the starchy endosperm of a grain is induced by mechanical stress due to the high humidity gradient inside the kernel and thermal stress. The fissure is a large internal fracture usually found to be perpendicular to the long axis of the grain [126]. The drying rate, which is a function of drying temperature and humidity, is the main cause of fissures [17,32,120]. The process of fissuring also continues after drying. Most fissuring occurs within 48 h after drying, but additional fissures develop at a low rate for another 72 h thereafter [65]. In microwave drying, stress cracking can be even more pronounced due to superposition of the pressure gradient that may build up within the material under certain drying conditions [141]. In the case of wheat, it also depends on the variety

[64]. The high-humidity air damages grains to a lesser extent than low-humidity air. Grains are severely damaged by high drying temperatures [130].

In the case of plant materials also, cracks are formed. At higher drying rates, the outer layers of the material becomes rigid and the final volume is fixed early in the drying process. As drying proceeds, the tissues split and rupture internally forming an open structure, and cracks are formed in the inner structure. When the interior finally dries and shrinks, the internal stresses pull the tissue apart [147]. Initial structure before drying can also create different extent of cracks, both inside as well as on the surface.

18.5.10 Rehydration

Rehydration is a process of moistening dry material. It is mostly done by applying an abundant amount of water. In most cases, dried foods are soaked in water before cooking or consumption, thus rehydration is one of the important quality criteria. In practice, most of the changes during drying are irreversible and rehydration cannot be considered simply as a process reversible to dehydration [69]. In general, absorption of water is fast at the beginning and thereafter slows down. This rapid moisture uptake is due to surface and capillary suction. Rahman and Perera [107], and Lewicki [69] reviewed the factors affecting the rehydration process. The factors are porosity, capillaries and cavities near the surface, temperature, trapped air bubbles, amorphous–crystalline state, soluble solids, dryness, anions, and pH of the soaking water. Porosity, and capillaries and cavities near the surface enhance the rehydration process, whereas the presence of trapped air bubbles is a major obstacle to the invasion of the fluid. Until the void or air cavities are filled with water, water penetrates to the material through its solid phase. In general, temperature strongly increases the early stages of water rehydration. There is a resistance of crystalline structures to salvation, whereas amorphous regions hydrate fast. The presence of anions in water affects volume increase during water absorption.

18.5.11 Volatile Development or Retention

In addition to physical changes, drying generates flavor or releases flavor from the foods. Drying changes the composition of volatiles by evaporating most volatiles and forming new volatile odor compounds by chemical reactions [72,143]. Such changes in volatiles might affect the aroma of fresh foods after drying, such as off-flavors were produced in peanut when drying air temperatures were above 35°C. In the case of peanut, they observed that the amount of off-flavor detected appeared to be a function of drying air temperature, moisture content, and off-flavor was likely to occur in immature peanuts than in mature peanuts [87]. Off-flavors resulting from high-temperature drying can be passed on to peanut butter and roasted peanuts. Acetaldehyde and ethyl acetate may be better indicators of off-flavor. High-temperature drying of pasta also leads to off-color and off-flavor [110].

A substantial volatile loss occurred during the first three stages of spray drying, and there should be zero or very little loss of volatiles during the fourth stage due to selective diffusion [62]. Losses can occur during atomization, from undisturbed drops, and as a result of morphological development. Several factors affect volatile retention, including control of atomizer pressure or rotation speed, choice of spray angle, configuration of air input, alteration of air temperature profile, feed concentration, presence of an oil phase and suspended solids, foaming of the feed, feed composition, surfactant, and steam blanketing of the atomizer [60–62]. The retention increased with increasing initial concentration of solids, increasing air temperature and velocity, and decreasing humidity. This is due to the selective diffusion mechanism, when surface water content is reduced sufficiently so that the diffusion coefficients of volatile substances become substantially lower than that of water [60,61].

18.5.12 Solubility

Many factors affect solubility, including processing conditions, storage conditions, composition, pH, density, and particle size. It was found that an increase in drying temperature is accompanied by increasing protein denaturation, which decreases solubility. Thus, more protein is denatured and solubility decreased [86]. Removal of water by evaporation results in the formation of an amorphous state.

18.5.13 Caking and Stickiness

Caking and stickiness of powders, desirable or undesirable, occur in dried products. Caking is desirable for tablet formation and undesirable when a dry free-flowing material is required. To reduce caking during drying, a logical option is to dry rapidly so that the moisture content drops to a level where caking is inhibited. The rapid drying will form a crust, which may be undesirable, thus product optimization or solutes in product formulation may be considered. Tendencies to form surface folds on particles during spray drying are governed by the viscosity of the concentrated solution. Stickiness and agglomeration tendencies also depend upon the viscosity of the concentrated solution, surface tension, particle size, and exposure time [61]. For viscosities below the critical value, stickiness usually occurs. The predicted critical viscosity was within the range of 10^8–10^{10} Pa s. The mechanism of sticking and agglomeration was postulated through viscous flow driven by surface tension and forming bridges between particles [31]. Adhikari et al. [4] presented a complete review on stickiness in foods, including mechanisms and factors controlling the process. The main factors affecting stickiness are temperature, viscosity, and water, followed by low-molecular sugars, organic acids, and compaction or pressure. The use of a glass transition temperature-based model provides a rational basis for understanding and characterizing the stickiness of many foods.

18.5.14 Texture

Factors that affect texture include moisture content, composition, variety or species, pH, product history (maturation or age), and sample dimensions. Texture is also dependent on the method of dehydration and pretreatments. Purslow [99] stated that meat texture is affected by the structure of the solid matrix. He concluded that it is important to have a fundamental understanding of the fracture behavior of meat and how it relates to the structure of the material. Stanley [132] stated that many researchers now believe the major structural factors affecting meat texture are associated with connective tissues and myofibrillar proteins. Moreover, two other components—muscle membranes and water—also deserve consideration not because of their inherent physical properties, but rather as a result of the indirect influence they have on the physical properties. It should be noted that sarcoplasmic proteins could be important for the same reason, although little information on their role is available. He suggested that these structures merit particular attention.

Kuprianoff [66] referred to the possible adverse effects of removing bound water from foods as (i) denaturation of protein by concentration of the solutes, (ii) irreversible structural changes leading to textural modification upon rehydration, and (iii) storage stability problems. Stanley [132] stated that the water-holding capacity of muscle is related to its sorption properties. The bound water in the muscle is primarily a result of its association with the myofibrillar proteins as indicated by Wismer-Pedersen [151]. Protein–water interactions significantly affect the physical properties of meat [46]. Changes in water-holding capacity are closely related to pH and the nature of muscle proteins.

18.5.15 Vitamins Retention

In general, losses of B vitamins are usually less than 10% in dried foods. Dried foods do not greatly contribute to dietary requirements for thiamin, folic acid, and vitamin B-6. Although vitamin C is largely destroyed during drying due to heating, meat per se is not a good source [22]. From nonfatty vegetables, such as cabbage, as much water as possible should be removed, because this helps to conserve ascorbic acid. The loss of vitamin A and ascorbic acid in dried products could be avoided in the absence of oxygen. Even though most amino acids are fairly resistant to heating–drying, lysine is quite heat labile and likely to be borderline or low in the diet of humans and especially so in developing countries where high-quality animal proteins are scarce and expensive [34].

18.5.16 Color Retention or Development

High temperature and long drying time degrade a product's original color. Color in foods can be preserved by minimal heat exposure or applying high temperature and short time with pH adjustment.

Water activity is one of the important factors degrading chlorophyll. Another cause of color degradation may be due to enzymatic browning causing rapid darkening, mainly of the leafy portions. The formation of dark pigments via enzymatic browning is initiated by the enzyme polyphenol oxidase (PPO). Another reason for discoloration is photooxidation of pigments, caused by light in combination with oxygen.

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