Chapter 17
Conventional and Advanced Thermal Processing Technologies for Enhancing Food Safety

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17.1 Introduction

Every year billions of people are at risk, and millions of people fall ill, and many die because of consuming unsafe food (WHO 2015). Though the detailed data on the economic cost of food-borne illnesses around the world is largely missing, the annual cost of food-borne illnesses in the United States alone is about $55.5 billion, estimated though a conservative economic approach (Scharff 2015). Thus, food-borne illnesses cause not only morbidity and mortality but also a significant impediment to socio-economic developments worldwide. Likewise, severe food-borne illnesses can cause reduced life expectancy and disabilities that affect the quality of life for the affected people (WHO 2015). The severity of risks associated with food contamination shows that food safety requires great concern in food production and processing. Food safety involves considering important factors such as microbial hazards, food chemistry, toxicology, processing capacity, process reactions, product and package interactions, and product stability over time. In addition to sufficient availability of foods, consumers expect the food to be produced in a sanitary manner and is safe to eat (Schoenfuss and Lillemo 2014). Thus, consumers require primarily safe foods in each mouthful consumed that are minimally processed and have freshness (Tapia et al. 2004). The government food regulatory bodies around the world are striving hard to ensure maximum food safety for its populace. Pasteurization and sterilization are the processes generally applied to destroy or inactivate microorganisms in foods to enhance food safety and storage life (Chandrasekaran et al. 2013).

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In addition to the microbial safety, food also needs to be safe from allergenic components. About 6–8% of children and 2–3% of adults around the world have food allergies, and allergic reactions to foods can be life-threatening (Umasunthar et al. 2013). Therefore, technologies are required to reduce the level of allergens in foods so as to ensure food safety for all.

Foods that are intended for long-term use must be processed using thermal or non-thermal technologies, or a combination of them, and safely stored. The objective of food processing is to produce a safe and nutritious product with acceptable quality attributes for the consumers. Since the thermal destruction of pathogens is the most effective method to ensure food safety (Dev et al. 2012), thermal treatment is one of the most traditionally and commonly applied methods for pasteurization and sterilization of foods. Thermal treatments not only destroy microorganisms and enzymes to prolong the shelf life of food, but also create acceptable taste, aroma, and appearance of food products (Kumar and Sandeep 2014).

For heat treatments, convection, conduction, and radiation are the three fundamental modes of heat transfer. Heating systems such as direct steam injection or steam infusion, retorts, heat exchangers, dielectric heating, and the combination of these systems are generally applied for blanching, pasteurization, hot filling, drying, evaporation, and sterilization of foods (Kumar and Sandeep 2014; Pereira and Vicente 2010). Thermal treatment of liquid foods is highly effective with conventional and advanced methods. However, thermal treatment of solid foods with low moisture content is challenging with both conventional and advanced methods due to increased resistance of microorganisms at lower water activity. Similarly, pasteurization and sterilization of packaged-foods using conventional methods are highly inefficient because heat has to transfer from the food surface to the interior of the foods. Also, the nutritional and sensory qualities of foods exposed to high-temperature treatment are significantly reduced. Currently, the demand for processed foods that retain their fresh taste and quality is increasing worldwide. Therefore, researchers and people in the food industry are working towards the development of advanced technologies for the processing of food (Neetoo and Chen 2014).

Investigators are developing new methods to improve the heat and mass transfer that involve conduction and convection mechanisms. Thermal processes which include the use of microwaves and radiofrequency, ohmic heating, and infrared irradiation are among the advanced technologies currently available for food processing. Compared to conventional technologies, the advanced technologies have reduced environmental footprint with high energy efficiency, reduced water consumption, and reduced emissions of greenhouse gases (Pereira and Vicente 2010). The increasing attention on the food safety and the efforts to develop new processing technologies to ensure food safety is evident from the increase in the number of research (journal articles, book chapters, conference paper, and review articles) articles published on these topics in recent years. Bibliometric analyses show that investigations on ‘food safety’ and ‘advanced thermal treatments’ have received increasing attention since the 1990s (Elsevier 2019). The trend in the number of research documents published every year since 2003 in the English language on the various aspects of “food safety” and the use of advanced thermal

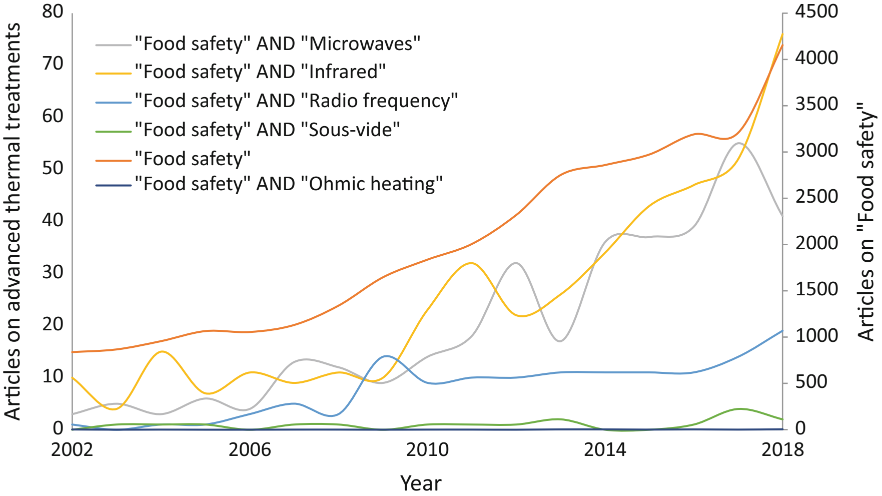

Fig. 17.1 Number of research articles published in English language on "Food Safety" and advanced thermal treatments during 2003–2018 (Elsevier 2019)

treatments to enhance food safety, is shown in Fig. 17.1. The research and development in the advanced thermal processing technologies for ensuring food safety are discussed in this chapter.

17.2 Enhancement of Heat Transfer in Conventional Heating Methods

Conventional technologies for the thermal processing of foods include retorting and heat exchangers. In these technologies, heat is transferred to the surface of food materials through conduction, convection and radiation mechanisms. Retorting technology requires the use of large amount of water and the heat transfer is inefficient in these methods (May 2001; Emond 2001). Therefore, investigations are being carried out to enhance the heat transfer in conventional heating methods. Particle to particle heat transfer is an advanced method of heat transfer involving the conduction and convection mechanisms. This method has great potential and is particularly useful for heat treatment of granular food materials such as grains and seeds (Sotocinal et al. 1997a). Because air has been used as a medium for heat transfer into the granular foods, the heat transfer is inefficient, especially when the hot-air becomes saturated with moisture from humid granular foods such as shelled corn (Sibley and Raghavan 1985). The use of the solid granular inert medium such as sand or salt for heat transfer can enhance the efficiency and the rate of food processing (Raghavan and Harper 1974). The use of molecular sieves has also been investigated for the enhanced heat transfer in the drying of grains such as corn. Molecular sieves are materials with selective adsorption properties that can separate components of a mixture based on molecular size and shape differences. Examples of molecular sieves include zeolites and silicates (Szostak 1989). Studies have shown that the molecular sieves are better than salts for the drying of grains (Raghavan et al. 1988).

Several designs of particle-particle heat transfer have been developed by researchers (Sotocinal et al. 1997b) and the thermodynamics and the associated heat transfer mechanisms have been extensively studied (Raghavan and Pannu 1986; Raghavan et al. 1974). A combination of air and solid granular inert medium with continuous agitation and mixing of the media can further enhance the heat transfer to food materials. The agitation and mixing of media with the food material can be achieved through the rotation of the container or fluidization of the mixture. The media and food can be separated at the end of the operation and the media returned to the beginning of the process in a batch or continuous mode. This will ensure that the food is not contaminated with the heat transfer media. Complete immersion of food in the heat transfer media provide uniform heating of food and significantly enhances the rate of heat transfer that results in faster processing of food (Richard and Raghavan 1980).

This technique discovered and adapted decades ago is very useful at the current time for better efficiency in the processing steps and the use of this approach can contribute to reducing greenhouse gas emissions into the atmosphere.

Recently, solid nanoparticles such as Al_2O_3, Cu, CuO, SiO, TiO, etc. are being investigated for enhanced heat transfer in convective thermal processes. Incorporation of nanoparticles can significantly enhance the heat transfer capabilities of conventional heat transfer fluids such as oil and water. Further investigations in this area are required to understand the mechanisms of the movements and the behavior of the nanoparticles in the heating process (Kakaç and Pramuanjaroenkij 2009).

17.3 Dielectric Heating Technologies Using Radio Frequency (RF) and Microwaves (MW)

Conventional heating methods take a longer time to inactivate the pathogens at the cold spot(s) of a food product. The non-uniform heating and the long processing time result in undesirable changes in foods especially in solid foods with lower moisture content (<50%, wet basis). Dielectric heating is much faster than the conventional heating, and the heat is generated within the body of material being heated. The heat generation can be controlled more quickly in dielectric heating than in the conventional heating methods. The shorter treatment time and lower temperature can minimize the degradation of nutrients and desirable quality attributes of the food. Current demand for packaged foods that can ensure safety by reducing the post-processing handling of food, increases the need for advanced technologies that can process packaged foods. Processing of packaged foods requires volumetric heating for increasing the internal temperature of foods to the required levels. However, the lack of suitable packaging materials makes the application of dielectric heating systems less successful for the processing of certain packed foods (Dev et al. 2012). These advantages and challenges have prompted significant research and development efforts in the dielectric heating technologies (Dev et al. 2012).

In general, the inactivation of microorganisms present in food occurs mainly due to the thermal effects of the dielectric heating treatments. Thermal treatments irreversibly denature enzymes, proteins, and nucleic acids that are essential for vegetative life and multiplication of microorganisms (Cebrián et al. 2017). If the processing is carried out in closed containers or packages, the steam generated inside will add to the lethality of the process and results in increased mortality of microorganisms (Dev et al. 2012).

Destruction or inactivation of microorganisms and enzymes by dielectric heating was explained by theories like selective heating, electroporation, cell membrane rupture, and magnetic field coupling (Kozempel et al. 1998). The selective heating mechanism involves the heating of microorganisms to a higher temperature than that of the foods and the surrounding medium. The electroporation mechanism involves the generation of high electrical potential across the cell membrane that causes the formation of pores and subsequent leakage of cellular materials. Cell membrane rupture occurs due to the high voltage and charges applied across the cell membrane. In magnetic field coupling, the electromagnetic energy will be coupled with the critical cell components such as DNA and proteins to disrupt the internal components of the cells (Kozempel et al. 1998; Chandrasekaran et al. 2013).

17.4 Microwave-Heating of Foods

Microwaves (MW) are electromagnetic radiations with a frequency range of 300 MHz to 300 GHz. However, domestic microwave appliances operate at 2.45 GHz frequency while industrial microwave systems operate at 915 MHz also. The penetration depth of 2.45 GHz microwaves is about 12 mm and that of 915 MHz microwaves is about 32 mm and it varies with the temperature of food. This limited penetration depth of microwaves causes heterogeneous heat distribution in foods, especially in the industrial applications (Herve et al. 1998).

The interaction of microwaves with dielectric materials results in the transformation of electrical energy into thermal energy within the dielectric materials. Microwave heating occurs through the dipolar rotation and ionic movement of molecules in foods. The dipolar molecules such as water rotates a million times per second as an effort to align with the oscillating electric field of microwaves. Similarly, ionic molecules present in foods do oscillatory migration due to the electromagnetic field of microwaves. These mechanisms cause the internal friction of molecules and thus heating of foods. In microwave heating, moisture content within the food may evaporate *in situ* and diffuses to the surface as vapor. When the temperature of the food reaches the boiling point of the solution in it, a positive pressure quickly develops within the food that forces the vapor and liquid to the surface. The efficiency of heat generation and rate of processing are dependent on such factors as dimensions (size and shape), composition (moisture, minerals, lipids, etc.), dielectric properties of foods, phase (liquid, solid) of food components, agitation of foods, available microwave power, and processing time. The dielectric properties of foods are influenced by temperature, moisture content, and the concentration of components such as salt and sugar. These properties change substantially during the heating of foods. In addition to dielectric properties, heat and mass transfer properties, microstructure, heat capacity, and heat of vaporization of food are also affected, and they significantly influence the outcome of the microwave heating process. These complex changes make it difficult to predict the outcome of the microwave heating (Scaman et al. 2014; Raaholt et al. 2014). In general, the knowledge of the dielectric properties of the materials involved can be used to obtain the appropriate conditions for microwave heating and desired lethality of the process (Chandrasekaran et al. 2013).

The microwave oven has become a common household appliance and large-scale microwave units have been increasingly used in the food processing industry as well. Microwave energy can be used for pasteurization, sterilization, tempering, dehydration, blanching, baking, coagulation, coating, gelatinization, puffing, roasting, and cooking of foods. Industrial processing of meats, fish, potatoes, and acidified vegetables are also done with the use of microwaves. Microwave heating results in no or minimally change in sensory qualities of the foods. Also, many studies have shown that MW processed foods have a better retention of nutrients than that in foods processed with conventional thermal processes.

Examples for industrial application of microwave heating include the pasteurization of pouch-packed meals and yogurts. Also, the pasteurization of packaged bread, cakes, and confectionary has been achieved using microwaves. Pasteurization using microwaves can be applied when the use of chemicals is not permitted for the inhibition of molds or when the application of chemicals significantly affects the volume and aroma of the products. Similarly, sterilization of packaged and pre-cooked foods has been achieved with the use of microwaves. Microwave pasteurization and sterilization of fluids and semi-fluids have been developed for industrial applications. Continuous processing is achieved by heating the pumpable foods during transportation through the tube. Foods such as milk, soups, sauces, and purees have been pasteurized or sterilized using microwaves (Raaholt et al. 2014).

Microwave thawing of frozen foods such as meat, fish, and butter has been applied in food industries worldwide to reduce the space and time required and control the growth of microorganisms in foods. By using microwaves, especially at 915 MHz frequency, the space requirement can be reduced by six times and the time required can be reduced to minutes or hours that can prevent the growth of microorganisms (Raaholt et al. 2014).

Drying is the most energy-intensive operation in the food industry, and the efficiency of drying is largely dependent on the effective transfer of energy into the foods for in-depth heat generation and moisture transfer. Microwave drying technology is efficient in providing in-depth heating that can lead to increased drying rates, shorter drying time, and removal of pathogens. It can reduce the space required for the processing of foods and improve the quality of food products. Foods dried with microwaves have less shrinkage, better color and rehydration properties, and high nutritional qualities than products dried using conventional methods (Raaholt et al. 2014). Additionally, the dehydration of partly-dried and porous solid materials is very challenging in conventional methods, and microwave heating is highly advantageous in the drying of these materials. Microwave heating has been used in the commercial drying of sugar cubes, potato slices, pasta, and vegetables. It has also been used in puffing of snacks, baking of half-baked thin foods such as biscuits, and drying of grains (Raaholt et al. 2014).

Microwaves have been used for pre-cooking of poultry, meat patties, and bacon to improve yield, improve product appearance, reduce nitrosamine formation, improve product stability, and increase the quality of rendered fat. Baking of foods using microwaves requires less time and space, and the color and structure of the products are more uniform than in the case of conventional baking. Microwave frying of doughnuts has led to shorter frying time and lower fat uptake than conventional frying methods (Raaholt et al. 2014).

Similarly, high-temperature-short-time sterilization using MW produces foods that are superior in quality than the foods produced through conventional sterilization processes (Add reference). The decontamination of powdered black pepper at different moisture levels was achieved using MW in continuous and intermittent mode applications and about 90% reduction in microbial load was achieved with 82% of volatile compounds retained in the process. Investigations have shown that MW-treated spices such as black pepper, oregano, red chili, rosemary, and sage have microbial loads within the limits set by the International Commission on Microbiological Specifications for foods (∗∗∗∗). . Also, the control of *Aspergillus parasiticus* which produces aflatoxin in hazelnuts was achieved by MW heating. The MW processing did not affect the sensory qualities of in-shell hazelnuts. Similar results were observed in the processing of walnuts and almonds (Dev et al. 2012).

Microwaves are increasingly used in the post-harvest processing of agricultural products. Stored cashew kernels infested with adult *Tribolium castaneum* were treated with microwaves for the removal of pests. More than 90% of the pests were killed after exposure to 80 °C for 180 minutes (McBratney et al. 2000). Similarly, barley seeds infected with the loose smut pathogen *Ustilago nuda* were treated with microwaves for the inactivation of the pathogen. The treatments were effective for the inactivation of the pathogen without significantly affecting the germination of the seeds (Stephenson et al. 1996). Researchers have used microwaves for the eradication of seed-borne pathogen *Diaporthe phaseolorum* in soybean seeds, and the microwave treatment did not significantly affect the viability of seed and the vigor of seedlings (Reddy et al. 1995). Also, the effect of microwaves on the degree of inactivation of *Fusarium graminearum* on wheat seeds, seed germination, and seedling vigor was investigated. The results have shown that the pathogen eradication increased with the increase in microwave power applied, but the seed viability and seedling vigor were adversely affected (Reddy et al. 1998).

Researchers have investigated the continuous pasteurization of water, milk, and cream using microwaves and found that milk was heated more rapidly than water because of the protein contents in milk. Among the components of milk, proteins heat up faster than fat and lactose (Kudra et al. 1991). Most of the commercial applications of MW sterilization are for the processing of liquid foods such as milk and juices and are applied by only a few industries. The non-uniform heating of solid foods and the lack of reliable methods to ensure the achievement of food safety standards results in slow adaptation of MW- sterilization process by the industries. Excessive heating of the corners and edge of foods occurs due to the localized concentration of the MW field in these areas. Use of 915 MHz, instead of 2450 MHz, for sterilization can result in a more uniform heating of foods due to the deeper penetration of MW into the foods. Researchers at Washington State University have been developing MW system for continuous sterilization of solid and semisolid foods using 915 MHz frequency (Tang et al. 2008). Among the applications of 915 MHz, MW sterilization of vacuum-packaged sliced beef in gravy and whey protein samples was investigated. The studies have shown that the 915 MHz single-mode system can be used for the sterilization of heterogenous foods such as fish in gravy in pouches and chicken meat in gravy in trays (Tang et al. 2008; Dev et al. 2012).

Development of commercial MW systems for continuous sterilization of pumpable foods such as vegetable purees have been investigated. Patents were issued for cylindrical applicator MW systems operating at 915 MHz. Similarly, pasteurization of in-shell eggs using 2450 MHz frequency with rotation of eggs, was investigated to achieve the different levels of pasteurization temperature required for the egg yolk (61.1 °C) and egg white (57.5 °C), as well as to overcome the challenges of pressure build-up and explosion of in-shell eggs during their processing with MW (Dev et al. 2012).

Microwave heating has also been used for the inactivation of allergens and protein inhibitors in foods such as soybeans (Vagadia et al. 2018). Investigations have shown that allergens in fruits, vegetables, and nuts can be inactivated by using microwaves. For example, allergens in celery, kiwi fruits, hazelnuts, cashew nuts, walnuts, and almonds were inactivated by treatment with microwaves (Vanga et al. 2017). The reactivity of potentially allergenic wheat gliadin was significantly increased after exposure to microwaves at 40 kJ. However, exposure to higher intensity of microwaves (80 kJ and 150 kJ) did not increase the reactivity of allergens. Therefore, further investigations are needed to develop optimized processing methods to reduce the allergenicity of foods. Altering the conformation of allergens through thermal and nonthermal processing can be explored to reduce the food allergy (Shriver and Yang 2011).

Many applications of microwaves have been claimed successful in laboratory and pilot scales, and the number of commercial implementations of such successful applications is slowly increasing. Microwave application is highly used for the sterilization of food packaging materials such as glass, plastic, and paper (Fito et al. 2004). However, some of the industrial applications of microwave heating were not successful due to the lack of conformity with the needs and specifications of the food processing plants. One of the main limitations of microwave processing for the sterilization of packed foods is the strict requirement of the absence of metallic content in foods. The non-uniform heating adversely affects the level of microbial inactivation (Fito et al. 2004). Moreover, the microwave equipment manufacturers have to design individual systems according to the requirements of industries that process different food materials. Also, the personnel in the food industry must be trained in handling the microwave equipment. However, the recent advances in modeling and simulation capabilities help in scaling up of successful applications of microwave processing methods. (Raaholt et al. 2014).

17.5 Radiofrequency Heating of Foods

The radiofrequency (RF) heating technology uses the electromagnetic radiation in the frequency range of 300 kHz to 300 MHz. The RF heating systems consist of the RF generator and electrodes. The RF generator creates an alternating electric field between the electrodes where food is placed for processing. The electric field alternates millions of times per second, which causes the dielectric molecules in the food to alternate in orientation while trying to align themselves with the alternating electric field. The rotation of molecules and the corresponding friction between the molecules and the space charge displacement cause heat generation within the food. The factors influencing the heat generation include the frequency and voltage applied, and the dielectric loss factor and dimensions of the food product (Tang et al. 2004).

RF can be applied to process large quantities of food products with high ionic conductivity. However, depending on the food characteristics and volume, each RF processing system requires specific design and tuning. To avoid interference with the telecommunications, only certain bands of radio frequency are legally allowed for industrial and scientific food processing applications. For example, 13.56 MHz, 27.12 MHz, and 40.68 MHz are allowed in North America for industrial RF processing of food. These frequencies have corresponding central wavelengths of 22 m, 11 m, and 7.3 m, respectively (Orsat and Raghavan 2014).

Early developments in RF pasteurization and sterilization were affected by the difficulty in measuring the temperature and pressure in electromagnetic fields. The development of fiber optic sensors for online measurement of temperature and pressure, infrared thermal imaging systems, dielectric properties measurement systems, chemical marker techniques, and computer simulation of electromagnetic fields have enabled the rapid development of RF technologies for the pasteurization and sterilization of foods (Tang et al. 2004).

Radiofrequency has been applied in the food processing industry for a long time for blanching, thawing, drying, baking, pasteurization, and sterilization. RF baking and post-baking processing of biscuits, crackers, and snack foods are widely used. Drying of grains and moisture leveling in finished products are also done with the help of RF. Moisture leveling is achieved in finished products because RF will produce more heat in wet regions than in the drier regions of the foods. This moisture leveling helps in improving the quality and consistency of the finished products (Neetoo and Chen 2014).

In one of the earliest investigations on the use of RF as a germicidal agent, the destructive effect of RF on *E. coli* was demonstrated and the use of electrolytes was suggested for enhanced bactericidal effects (Fleming 1944). The destruction of microbial cells is possible if heat is generated much faster in the cells than in the surrounding medium. Since most of the microbial cells bear a negative charge, the cells can be oscillating rapidly in an alternating electric field, and when the elastic limits of the cell structure exceeded, the cells will be ruptured to cause the death of the microorganisms (Orsat and Raghavan 2014).

Investigations have shown that the RF heating of apples and cherries kills pests but does not affect the sensory qualities of the fruits. Similarly, oranges treated for the control of Mediterranean fruit flies and persimmons fruits treated for the control of Mexican fruit fly larvae have shown no significant changes in qualities such as firmness, weight, total soluble solids, acidity, and volatiles. Vacuum-packed carrots treated with RF had higher qualities and extended shelf life than the carrots treated with conventional methods such as dipping in chlorinated or hot water (Orsat et al. 2001). The control of contamination by pathogenic bacteria such as *Salmonella, Escherichia coli*, and *Listeria monocytogenes* on alfalfa seeds, without affecting their germination, was achieved by using short-term RF treatments. Almonds were treated with RF to reduce contamination with *Salmonella* Enteritidis without affecting the nutritional qualities (Marra et al. 2015; Tang et al. 2004).

Pasteurization of sliced bread loaves using RF was reported by Cathcart et al. as early as 1947. RF pasteurization prevented mold growth and staling in bread loaves stored for 10 days at room temperature. It controls the growth of *Aspergillus* and *Penicillium* in bread loaves (Tang et al. 2004). Pasteurization of meat emulsion samples using RF can reduce the processing time by 79% when compared to steam pasteurization (Tang et al. 2004). RF heating of comminuted meats for the reduction of vegetative cells and spores of *Bacillus cereus* and *Clostridium perfringens* was also found as effective (Marra et al. 2015). RF heating was investigated to reduce microbial counts on fresh meats and chum salmon (*Oncorhynchus keta*) eggs. RF heating has also been used in control of *Clostridium botulinum* spores in foods. However, in some cases, the non-uniform heating of the surfaces of foods leads to an insufficient reduction in microbial counts. Increasing the salt content and the highest processing-temperature of the foods can increase the inactivation of microorganisms in processed foods (Tang et al. 2004; Orsat and Raghavan 2014).

Compared to conventional methods, RF treatment can produce juices (e. g., orange, peach, and quince juices) with better bacteriological and sensory qualities (Demeczky 1974). Studies have shown that RF heating can be successfully used for the inactivation of *Escherichia coli* and *Listeria* in milk under continuous laminar flow conditions (Awuah et al. 2005). Similarly, RF heating was used for sterilizing 6-pound trays of macaroni and cheese, and the treatment effect was compared with the conventional 90 minutes long retort process. RF treatment achieved the target sterilization within 30 minutes and it did not induce significant changes in color and flavor (Wang et al. 2003; Marra et al. 2015).

Mathematical modeling and computer simulation have been used for rapid development of RF systems for food processing. Finite element modeling (FEM) of RF pasteurization of in-shell eggs was carried out to determine the hot and cold spots generated in the material when the eggs were under different strengths of the electric field and in different orientations. The simulation results have shown that the in-shell eggs should be rotated inside the RF field to obtain uniform heating and proper pasteurization (Dev et al. 2012). Additionally, the continuous processing of foods with RF requires the adaptability of the system for different geometry of the foods. The change in geometry of the foods changes the RF coupling power. Therefore, continuous monitoring of the geometry of foods and the corresponding adaptation and moving of RF electrodes is required for continuous RF-based processing of foods (Dev et al. 2012). Computer-aided development of RF systems improved the heating uniformity and coupling of power into the applicators. Commercial and in-house developed software programs are available for modeling and simulation purposes. The correlation between simulated and experimental data is still a challenge because of the complexity of the underlying process and product behavior (Tang et al. 2004).

In addition to the application of RF to process high moisture containing foods, researchers have been investigating the control of pathogens in foods with low moisture content. RF pasteurization of almonds and peanut butter cracker sandwiches has been studied (Jiao et al. 2018). About 2–4 minutes of RF treatment could produce 5-log reduction of *Salmonella* in almonds (Gao et al. 2011). Similarly, about 1.5 minutes of RF treatment of creamy peanut butter resulted in log reduction of 4.29 log CFU/g for *S. Typhimurium* and 4.39 log CFU/g for *E. coli* O157:H7. Also, there was no significant effect of the RF treatment on the sensory qualities of the peanut butter and crackers (Ha et al. 2013). Treatment of wheat flour with RF resulted in 5–7 log reduction in *Salmonella* after 8.5–9 minutes of treatment (Villa-Rojas et al. 2017; Jiao et al. 2018).

17.6 Ohmic Heating of Foods

Ohmic heating is also known as Joule heating, electrical resistance heating, electro-conductive heating, and electro-heating. This process involves the passing of low-frequency (50–60 Hz) or high-frequency (up to 25–30 kHz) alternating electric currents through foods to generate heat. The application of low-frequency electricity requires the use of specially designed graphite electrodes to avoid electrolysis and metal dissolution into food. Stainless steel electrodes can be used if high-frequency electricity is used for Ohmic heating (Chen 2015). Ohmic heating was practiced in the 1930s for milk pasteurization, but due to the high cost of the process and the requirement of suitable inert electrode materials, Ohmic heating was not highly pursued until 1980s. Developments in areas such as power electronics and the availability of low-cost ohmic heaters have greatly advanced the improvement and refinement of ohmic heating technology. These developments have helped in the control of electrolytic reactions taking place at the electrodes during ohmic heating (Sastry 2004). Currently, it has been investigated for blanching, pre-heating, sterilization, and thawing of food materials. High-frequency power systems and online process control technology helps to incorporate ohmic heating into high-temperature short-time (HTST) processing of liquids and liquid foods containing particulates. Rapid heating, high-quality products, less fouling, and greater energy efficiency are some of the benefits of ohmic heating technology (Chen 2015).

Ohmic heating can be applied for the continuous processing of viscous foods and foods containing particulates. Large heating tubes with lower shear rates are used for the heating of fragile particles. The main parameter that influences the rate of ohmic heating is the electrical conductivity of foods which depends on temperature, ionic constituents of foods, the structure of foods, and electric field strength. Addition of salts and liquids increases the ionic concentration and thereby the electrical conductivity of solid foods. Thus, the foods can be soaked in saline solutions before ohmic heating for rapid processing (Goullieux and Pain 2014).

Ohmic heating has been applied to a wide variety of foods such as juices, sauces, meats, soups, liquid egg products, fruits, vegetables, and seafood. It can be used to sterilize foods and to produce high-quality shelf-stable processed foods. Foods processed with ohmic heating retained their texture and had high nutrient content, color, and flavor than the traditionally processed foods (Neetoo and Chen 2014). However, ohmic heating is suitable only for materials containing ions and is not suitable for food materials like oils. The difference in electric property between ingredients makes the control of the process very difficult. Also, the direct temperature measurement of the multiphase particles in a food product is challenging (Chen 2015).

Several investigations were carried out on the lethality of ohmic heating for microorganisms. The heat generated within food is largely responsible for the inactivation of microorganisms. Since ohmic heating is faster than conventional heating to increase the food temperature, foods can be sterilized in a short time with ohmic heating. The extent of microbial inactivation is dependent on the strength of electric field applied, treatment time, microorganism targeted, and food type (Goullieux and Pain 2014). Higher electric field strengths and longer treatment time results in greater reduction of microbial loads. The non-thermal effects of ohmic heating on microbial inactivation is caused by the electric current at low frequency (50- 60 Hz), which can lead to the accumulation of charges and forming pores on the cell wall of microorganisms. Investigations have found enlarged periplasmic space and uneven cell wall structure in *E. coli* cells after ohmic heating. The electroporation phenomenon was observed when yeast (such as *Saccharomyces cerevisiae*) cells were treated. The leakage of cellular contents was increased significantly with an increase in electric field strength (10–20 V/cm), and the electroporation of the cell membrane was irreversible (Goullieux and Pain 2014).

Inactivation of *E. coli* and *Bacillus subtilis* spores in saline water and orange juice was investigated with ohmic heating at a high alternating current electric field

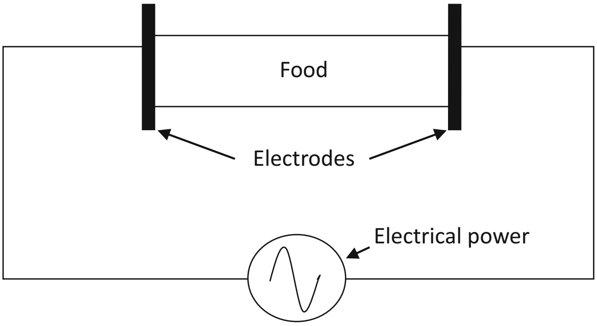

Fig. 17.2 Diagram of Ohmic heating system for food processing. (Adapted from Chen 2015)

(20 kHz, 7–17 kV/cm). About 5-log reduction of *E. coli* was observed when 0.1% saline water was heated to 74 °C using 20 kHz, 14 kV/cm electrical system (Uemura and Isobe 2002). Similarly, about 4-log reduction of *B. subtilis* spores was observed when orange juice was heated to 121 °C using 20 kHz, 16.3 kV/cm electrical system (Uemura and Isobe 2003). It has been postulated that the ohmic heating induces the leakage of ionic compounds such as calcium dipicolinic acid from the core, and denatures the enzymes on the coat, of bacterial spores. The leaked ionic compounds further increase the electrical conductivity of the spores to increase the destructive effect of ohmic heating (Goullieux and Pain 2014; Uemura and Isobe 2002; Uemura and Isobe 2003).

The nutritional quality of infant formula sterilized with ohmic heating was found as not significantly different from the infant formula sterilized with conventional methods such as ultra-high temperature for a short time (130 °C for 6 s). After the ohmic heating, the concentrations of Maillard reaction compounds such as furosine, carboxymethyl lysine, lactulosyl-lysine, fructosyl-lysine, pyrraline in infant formula were comparable with that of the infant formula sterilized with conventional methods. Also, the level of vitamin C was better preserved in infant formula processed using Ohmic heating (Roux et al. 2016). Therefore, ohmic heating can be applied to produce safe foods with high nutrients and vitamin levels (Goullieux and Pain 2014).

The configuration of the ohmic heating system (Fig. 17.2) needs to be adjusted depending on the type of foods to be processed. The flow behavior and electrical conductivities of the foods and particles need to be understood for better control of heating and to achieve homogenous temperature distributions in the foods. Modeling and simulation of the process help in designing ohmic heating systems that can provide maximum possible efficiency in sterilization and nutrient retention in foods. However, more work is needed to fully understand electrical conductivity, rheological properties, and particle sizes of food during ohmic heating. The changes in flow behaviors and electrical properties of solid-liquid mixtures, especially with large sized particles at high concentration, need to be understood for commercial applications of ohmic heating (Goullieux and Pain 2014).

17.7 Infrared Heating of Foods

Infrared (IR) is the electromagnetic radiation emitted due to the vibrational and rotational movements of molecules in a hot source. It is predominantly responsible as radiant energy for the heating effect of sunlight. The heating effect of infrared has been used traditionally for the thermal processing of foods to ensure safety and shelf life. Thus, the application of IR heat is one of the oldest methods of food processing. The IR radiation spectrum is categorized mainly into three bands, viz. near infrared (NIR) radiation with wavelength in the range of 0.75–3 μm, mid-infrared (MIR) radiation with wavelength in the range of 3–25 μm, and far-infrared (FIR) radiation with wavelength in the range of 25–1000 μm. The IR radiation band of 2.5–200 μm is generally used in the advanced methods for food processing (Das and Das 2015).

The commercially used IR heating equipment consists of a radiator which radiates IR in all directions and a reflector (waveguide) which directs the IR to a target such as food (Fig. 17.3). Foods absorb, transmit, and reflect the IR radiation falling on it. The extent of IR absorption depends on the composition and the radiation properties such as absorptivity, reflectivity, and transmissivity of foods. Water and the various organic molecules such as proteins, lipids, and starch in food absorb IR radiations at different wavelengths. Proteins absorb IR in the range of 3–4 μm and 6–9 μm, lipids absorb IR in the range of 3–4 μm, 6 μm, and 9–10 μm, and sugars absorb IR in the range of 3 μm and 7–10 μm. The molecules that absorbed IR radiation will generate heat through stretching vibrations (Das and Das 2015).

IR processing can be applied to provide a high amount of heat directly into the food within a short time, without heating the surrounding air. Compared to conventional methods, the heating efficiency of IR heating is very high and changes in the quality of the foods are minimal (Pan et al. 2014). Compared to microwave and radiofrequency technologies, IR heating can provide more uniform heating of the surface and core of foods. The depth of penetration of IR into foods is in the range of

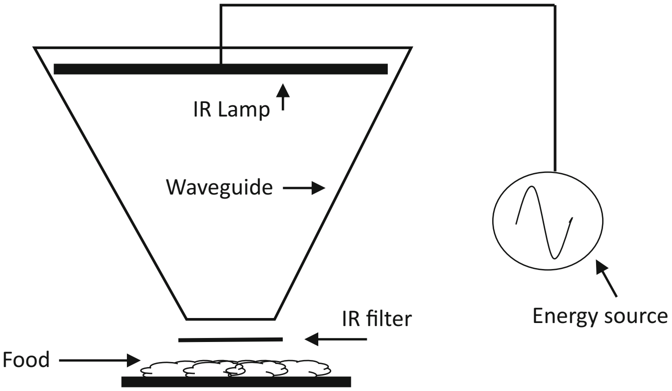

Fig. 17.3 Schematic of IR heating system for food processing. (Adapted from Jun and Irudayaraj (2003)))

1–18 mm which significantly influences the temperature and moisture level of the final products. Shorter penetrating IR significantly increases the surface temperature of foods. Generally, IR processing is considered a safer and cleaner method than many of the conventional methods (Neetoo and Chen 2014; Das and Das 2015).

IR heating has been applied for baking, drying, and cooking of foods with smooth surfaces and modest thickness. It has also been applied for the surface pasteurization of bakery products, decontamination of packaging materials, and thawing of frozen foods. The IR heating was successfully used for drying of shrimps, barley, and oysters. Similarly, it has been investigated for the cooking of in-shell eggs and bread baking. The rehydration capacity of foods dried through IR heating was found to be higher than the foods dried using microwave heating and hot air methods. As in the case of other processing methods, IR heating also requires strict process controls because exposure of foods to IR for longer duration results in discoloration of the food surfaces (Neetoo and Chen 2014).

IR heating has been used for pasteurization and sterilization of foods, and the process has high thermal efficiency and fast heating rate than the conventional heating process using steam. IR radiation is absorbed by the water molecules in microorganisms that lead to the rapid increase in cell temperature and consequent inactivation and death of all types of microorganisms. IR heating damages DNA, RNA, ribosome, cell envelope, and proteins in microorganisms. IR treatments can destroy all vegetative cells and spores of bacteria, yeast, and molds in solid and liquid foods based on the treatment conditions. The efficacy of IR sterilization and pasteurization is dependent on the IR power level applied, temperature of the food, wavelength and bandwidth of the IR emitter, size and type of foods, nature and concentration of microorganisms present in food, and moisture content of foods (Das and Das 2015; Pan et al. 2014).

The efficacy of IR heating for enhancing food safety has been investigated for pathogen inactivation, sterilization of milk, decontamination of fruit surfaces, pasteurization of nuts, and disinfestation of grains (Pan et al. 2014). Packed solid dairy products such as cottage cheese in a plastic container were pasteurized with IR at 71 °C for 5 minutes to reduce the count of yeast and molds on the surface and about 1 cm deep. It improved the shelf-life of the product by 3–4 weeks when stored at 4 °C. Investigations have shown that, at a given temperature, IR heating is more effective than conductive heat against *E. coli* and therefore, a given pasteurization target can be achieved faster with the use of IR. The IR heating method has been successfully applied to decontaminate *Bacillus subtilis* from wheat, *Rhodotorula mucilaginosa* from fig fruits, *Staphylococcus aureus* from milk, *Listeria monocytogenes* from hot dogs, *Salmonella* Enteritidis from almonds, *Aspergillus niger* and *Fusarium proliferatum* from corn meal, and *Bacillus cereus* spores from paprika powder. Among the different methods investigated for the pasteurization and decontamination of *Salmonella enterica* serovar Enteritidis, IR heating effectively decontaminated and preserved the quality of raw almond kernels (Das and Das 2015; Pan et al. 2014).

The IR processing conditions recommended for the pasteurization of raw almonds were heating of almonds to 100–120 °C and holding at 90–100 °C for

5–10 minutes. In addition to the inactivation of *Salmonella* species, these conditions provide over 5.5 log reductions of *Pediococcus* bacteria also. The IR heating methods can replace the chemical methods of using methyl bromide for disinfesting freshly harvested and stored rice. Also, these treatments reduce the moisture content which helps in the milling of rice. The recommended temperature for killing all moths in freshly harvested rice is 60 °C, and for stored rough rice it is 50 °C, for 1 minute (Pan et al. 2014).

In addition to the pasteurization of foods, IR heating was also used to decontaminate the food-contact surfaces to eliminate microorganisms and thereby improving the shelf-life of foods. For example, baking trays are sterilized using IR before the dough was put on them. Additionally, the selective heating of fungal spores was investigated by applying IR in the range of wavelengths suitable for the denaturation of proteins. Selective IR heating had a higher degree of lethality than the nonselective irradiation process. Moreover, the systems equipped with emitters that can release IR in the absorption band of water in food can be more effective in food processing. However, successful commercial applications of IR heating are still a challenge due to the small cost recovery, productivity issues, and nonuniform quality of IR-processed products (Das and Das 2015).

17.8 Sous-Vide Processing of Foods

Sous-vide processing involves heating of vacuum-packaged food under low-temperatures (65–95 °C) for 7–8 hours and storing the processed food in the refrigerator at (0–3 °C). This technology is particularly applied to process meat, fish, ready-to-eat meals, etc., in the food service industry (Park et al. 2014). It is considered as one of the delicate and healthy methods of food processing. Most of the nutritional contents and flavors of the food are preserved in this processing method through the control of heat, oxygen level, and moisture content. The reduced oxidation helps in maintaining the qualities of essential polyunsaturated fatty acids in foods. Sous-vide cooked foods have desirable organoleptic properties such as fresh-like texture, good flavors, and wholesomeness that are appealing to consumers (Neetoo and Chen 2014).

Sous-vide processing was reported to reduce the counts of pathogenic bacteria such as *Staphylococcus aureus*, *Bacillus cereus*, *Clostridium perfringens*, and *Listeria monocytogenes* to below detectable levels on fish samples and extend the shelf-life of the processed fish to more than 45 days when stored at 2 °C. Compared to conventionally cooked fish cakes, the sous-vide cooked fish cakes had improved microbial safety and an eightfold increase in shelf-life when stored at 3 °C. Similarly, the addition of salts such as calcium lactate and sodium lactate had completely inhibited the growth of *Bacillus cereus* on sous-vide processed beef goulash samples

(Neetoo and Chen 2014). However, the low-temperature applied in sous-vide processing does not always inactivate harmful bacterial spores, and the vacuum conditions may support the survival of anaerobic bacteria such as *Clostridium botulinum* (Park et al. 2014).

Though the sous-vide processing of foods is appealing to consumers, the industry must use high-quality ingredients to start with and the environment should be properly sterilized to prevent the initial contamination of the foods. Also, the strict monitoring and control of the process temperature and time required to inactivate the many possible pathogens and the need for proper storage conditions to keep the processed foods for long-term use limit the applicability of in sous-vide processing in the food industry and home kitchens (Neetoo and Chen 2014).

17.9 Combination of Thermal Methods for Food Safety

A summary of the different thermal technologies and their applications for ensuring food safety discussed in this chapter is given in Table 17.1. No single technology is applicable to all food types and process requirements. Ensuring food safety throughout the supply chain requires effective and efficient strategies that involve combining multiple technologies to inactivate pathogens in foods and increase product stability. Though many dielectric technologies have been developed for the processing of food, the commercial implementation of these techniques is very limited. Physicochemical damages to the foods such as fresh fruits subjected to thermal treatments, nonuniform heating of solid foods, and the post-processing loss of quality of foods lead to investigations on combining different methods of food safety to compensate for the disadvantages and make use of the advantages of the individual methods (Dev et al. 2012). Some of the combined methods investigated for enhanced food safety are discussed in this section.

Radiofrequency heating combined with hot-air treatment was investigated to reduce mold growth in packaged bread loaves. Vacuum-packed ham slices were pasteurized by Orsat et al. (2004) using RF with 600 W at 27.12 MHz and found that the storability of vacuum-packed hams was improved by decreasing the bacterial load and moisture loss. The sensory qualities and product acceptance of the ham slices were not significantly changed after the RF treatments (Marra et al. 2015; Orsat et al. 2004). Advances in the IR-based thermal imaging technology have been helped in the development of RF-based systems for food quality assurance and safety assessment. Applications of thermal imaging include temperature validation, detection of the bruise and foreign bodies, and evaluation of product quality in food processing (Gowen et al. 2010).

Table 17.1 Summary of advanced thermal treatments investigated for food safety

Process	Process parameters	Advantages	Disadvantages	Examples of food safety applications
Dielectric heating (microwave and Radiofrequency)	Composition, dielectric properties, dimensions, size, and mixing and agitation of food and media Power level, and frequency of MW or RF applied Processing time	Volumetric and faster heating Quick control of heating is possible Can be applied to packed foods High retention of nutrients in food	Non-uniform heating of heterogeneous solid foods Unpredictable process outcome Non-metallic food-containers required High capital investment required	Pasteurization and sterilization of milk (*E. coli* and *Listeria*) (Awuah et al. 2005), bread (*Penicillium*) (Liu et al. 2011), scrambled egg (*Clostridium sporogenes*) (Luechapattanaporn et al. 2005), almonds (*Salmonella enteritidis*) (Gao et al. 2011), alfalfa seeds (*Salmonella, E. coli*, and *Listeria monocytogenes*) (Nelson et al. 2003). Pest removal from cashew nut (*Tribolium castaneum*) (McBratney et al. 2000), walnut (orangeworm (*Amyelois transitella*)) (Wang et al. 2007), etc.
Infrared heating	Wavelength of IR radiation Composition, size, and radiation properties of food Processing time	Uniform surface heating Processing of packed-foods High retention of nutrients in food Good for the sterilization of food contact surfaces	High capital cost required Non-uniform product quality	Decontamination of *Bacillus subtilis* from wheat (Daisuke et al. 2001), *Rhodotorula mucilaginosa* from fig fruits (Hamanaka et al. 2011), *Staphylococcus aureus* from milk (Krishnamurthy et al. 2008), *Listeria monocytogenes* from hot dogs (Huang and Sites 2008), *Enterococcus faecium* from almonds (Yang et al. 2010), *Aspergillus niger* from corn

(continued)

Table 17.1 (continued)

Process	Process parameters	Advantages	Disadvantages	Examples of food safety applications
				meal (Jun and Irudayaraj 2004), *Bacillus cereus* spores from paprika powder (Staack et al. 2008), etc.
Ohmic heating	Electrical conductivity, ionic concentration, and structure of food Electric field strength Temperature Processing time Configuration of the system	Heating of particulate foods Retention of nutrients and sensory qualities of food	Not suitable for oils Non-uniform heating of heterogeneous solid foods containing ingredients with different electrical properties	Inactivation of *E. coli in saline water* (Uemura and Isobe 2002) and *Bacillus subtilis* in orange juice (Uemura and Isobe 2003).
Sous-vide heating	Vacuum packing of food Temperature Processing time	High retention of nutrients Reduced oxidation Desirable organoleptic properties and wholesomeness of processed foods	Low temperature insufficient for inactivation of all pathogens (e.g., *Clostridium botulinum*)	Control of *Staphylococcus aureus*, *Bacillus cereus*, *Clostridium perfringens*, and *Listeria monocytogenes on rainbow trout* (González-Fandos et al. 2004)

17.10 Summary and Conclusions

The application of advanced thermal technologies holds the potential for producing high-quality and safe food products. A summary of the different thermal technologies and their applications for ensuring food safety discussed in this chapter is given in Table 17.1. It can be seen that, each of the technologies available for food processing is applicable to particular food types and process requirements. Also, ensuring food safety throughout the supply chain requires effective and efficient strategies that involve combining multiple technologies to inactivate pathogens in foods and increase product stability. Despite the many advantages and successful application of advanced thermal technologies at laboratory scale to ensure food safety, the industrial applications of these technologies are limited due to the relatively high capital cost required and the nonuniform heating obtained in solid foods (Dev et al. 2012). Physicochemical damages to the foods such as fresh fruits subjected to thermal treatments, nonuniform heating of solid foods, and the post-processing loss of quality of foods lead to investigations on combining different methods of food safety to compensate for the disadvantages and make use of the advantages of the individual methods (Dev et al. 2012).

Utilization of the advantages of each technology while minimizing and eliminating the disadvantages of them is an important engineering challenge for the researchers and people in the food industry. Advance in computer-aided modeling and simulation of the thermal pasteurization and sterilization of different food products will help in developing highly efficient technologies to meet the food safety standards in the food industry. Methods should be developed for inducing appropriate conformational changes to the allergenic components of the foods to ensure food safety for all.

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