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Review article

Microwave processing technology for food safety and quality: A review

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Abstract

Microwave processing is a novel heating method which has been applied in the industrial and agricultural sectors, especially in the food industry. The use of microwave heating presents many advantages involving rapid heating, high temperature, short cooking time, clean energy and low operating cost. In addition, this technique can improve the safety and qualities of food products. This paper discusses industrial and domestic microwave applications, including sterilization, pasteurization, thawing, puffing, atmospheric drying, vacuum drying, freeze drying, blanching, frying, baking and extraction processes, applied in various types of foods from the viewpoint of quality and safety. Food innovations based on microwave technology are presented. Microwave technology is predicted as a first alternative technology and to become more popular in the near future.

Introduction

A microwave is an electromagnetic wave with a frequency band between 300 MHz and 300 GHz that forms part of the electromagnetic spectrum that is non-ionizing radiation (Regier et al., 2017a). Microwaved foods are safe for consumption since microwave energy is transformed to heat immediately and no radioactive substance is generated (Occupational Safety and Health Administration [OSHA], 2012). Microwave processing technology has been considered novel thermal processing and is now increasingly used in food industries and households (Meda et al., 2017). There are many microwave applications, including sterilization, pasteurization, thawing, puffing, atmospheric drying, vacuum drying, freeze drying, blanching, frying, baking and extraction (Gupta and Leong, 2007) with various advantages (Table 1). Microwave technology is rated as the first main technology that is applied presently and in the next 5 yr in North America, followed by in Europe in the next 10 yr, with the main drivers being higher quality products, product safety and extension of shelf life (Jermann et al., 2015).

The potential advantages of microwave heating have resulted in it being considered as an alternative treatment to conventional heating (Benlloch-Tinoco et al., 2013). The energy in conventional thermal processing is transferred to the surface of food items by convection and then heat is transferred internally by conduction; however, thermal conductivity in food is very low which causes slow heating, whereas microwave energy is delivered to food directly via interaction between the food and the electromagnetic field. Therefore,

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Table 1 Potential advantages of microwave processing technology

Microwave technique	Advantages	References
Sterilization, pasteurization	Enhances quality, storage time and safety.	Tang (2015); Chandrasekaran et al. (2013); Auksornsri and Songsermpong (2017)
Thawing	Improves quality, less drip loss, reduced textural damage and discoloration of frozen foods.	James et al. (2017)
Puffing	Replaces frying for non-fried foods.	Rakesh and Datta (2011); Nguyen et al. (2013)
Atmospheric drying	Produces instant foods with short processing time.	Pongpichaiudom and Songsermpong (2018)
Vacuum drying	Prevents oxidation, maintains good color, texture, flavor and nutrition of dried products.	Chandrasekaran et al. (2013)
Freeze drying	Produces highest quality of dried products.	Zhang et al. (2006)
Blanching	Uses less energy and short time to inactivate enzymes in food components, maintains color of products.	Chandrasekaran et al. (2013)
Frying, baking, extraction	Saves time and energy, achieves high retention of nutrients, increases extracted bioactive compounds	Orsat et al. (2017)

using microwaves will achieve rapid and uniform heating because heat can be generated throughout the volume of the food and the energy transition is not dependent on the diffusion of heat from the surfaces. In addition, the cost of energy in microwave processing is lower and the sensory, nutrient and functional properties of the food products are greater. For example, it has been reported that microwave heating could destroy lipase and lipoxygenase activity in rice bran, while retaining the antioxidant capacity (Pongrat and Songsermpong, 2019).

Microwave technology has been applied in developed countries since World War II and developing countries are increasingly using it. Normally, four frequencies are allowed for use in industrial, scientific and medical areas. However, 2,450 MHz is used for home microwave ovens and 915 MHz is used for industrial microwave ovens (Tang, 2015). It has been shown that a magnetron at 2,450 MHz generates many frequency spectra that caused inconsistent heating, while a 915 MHz magnetron produced only one frequency spectrum which produced consistent heating (Chan and Reader, 2000; Resurreccion Jr et al., 2015). In busy, modern lifestyles, heating of chilled and frozen foods or even street food is most convenient, especially during the Covid-19 pandemic, when not only a short processing time but also the safety and quality of food items are required. Thus, it is confidently predicted that microwave technology will continue to be more convenient and necessary for current situations and in the future. Therefore, the aim of this review paper focused on the effects of microwave processing technology on the safety and quality of food products.

Microwave processing technology

Principle of microwave heating

Microwave heating, a thermal process, is an alternative conventional heating method in the food processing industry (Tang, 2015). In a microwave system the electromagnetic fields interact directly and rapidly with food components leading to internal and volumetric heating that overcome the slow heat transfer rate of the conventional thermal process in which convection and conduction heating are used (Auksornsri and Songsermpong, 2017).

In general, microwave energy is converted into heat caused by the absorption ability of the material being heated. The microwave heating mechanism in food materials is mainly dipolar rotation and ionic polarization with the presence of water and ions. When an electric field oscillates around food, the dipole water molecules in the food rotate and ion molecules move in the direction of the electric field. Because the electric field is high, rearrangement occurs in amounts of millions of times per second and creates internal friction of molecules, leading to volumetric heating of the food (Datta and Davidson, 2011).

Dielectric properties of foods

Dielectric properties are the main properties that show the ability of foods to transform microwave energy into heat (Muthukumarappan and Swamy, 2019). Dielectric properties include the dielectric constant, which is a physical parameter that indicates the ability to store electrical energy, and dielectric loss, which is an abstract parameter showing the ability to convert electrical energy into heat, as shown in Equation 1 (Chandrasekaran et al., 2013):

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1)$$

where ε' is the dielectric constant, ε'' is the dielectric loss and $j = \sqrt{-1}$. The ratio of the abstract part to the real part is presented by the loss tangent (tan δ), as shown in Equation 2:

$$\tan\delta = \frac{k''}{k'} = \frac{\varepsilon''}{\varepsilon'} \quad (2)$$

where k' is relative dielectric constant and k'' is relative dielectric loss. In which, $k' = \varepsilon' / \varepsilon_o$ and $k'' = \varepsilon'' / \varepsilon_o$ where ε_o is free space permittivity (ε_o= 8.854 x 10^{-12}F/m).

The penetration depth is the distance from the surface into the food of the microwave power and equals 1/e or 36.8% of the power at the surface. A frequency of 915 MHz has a greater penetration depth than 2,450 MHz (Tang, 2015).

Factors affecting dielectric properties of food products

The dielectric properties of foods are affected mainly by the frequency, temperature, moisture content and food composition (Resurreccion Jr et al., 2015). Dipole polarization is significant when the frequencies are higher than 1 GHz and the ionic losses are predominant when the frequencies are lower than 1 GHz (Ryynänen, 1995). Basically, the dielectric loss caused by reactions of substances in electromagnetic fields, including polar, electronic, atomic and Maxwell-Wagner equation (Equation 1) (Regier and Schubert, 2005). Normally, in food materials containing organic material, water and salt, increasing salt addition produces a higher dielectric loss at a particular frequency because ion, water and salt acts as conductors in the presence of an electromagnetic field (İçier and Baysal, 2004a). In moist foods, the dielectric properties increase when the frequency increases. In frozen food materials, the dielectric properties are low and might increase with an increase in the melting zone temperature due to high water content (Chandrasekaran et al., 2013)

At a frequency of 2,450 MHz, the dielectric constant and loss factor are lower than at 915 MHz. The dielectric constant of water with added salt is lower than that of water; however, the dielectric loss increases with increasing salt content in food (İçier and Baysal, 2004b). Fat and oil have very low values for the dielectric constant and dielectric loss. This knowledge can be applied in food formulation to make all components have similar dielectric properties. A high dielectric property in a food item can be lowered by adding fat and oil, while a low dielectric property can be increased by adding water and salt. It is expected that components with similar dielectric properties will have the same heating rate; thus, heating uniformity will be improved. Water has very high dielectric properties, whereas ice has very low dielectric properties. During defrosting, some ice becomes water while some ice remains intact, leading to different heating rates known as thermal runaway (Chandrasekaran et al., 2013).

Measurement of dielectric properties

Dielectric properties are measured using various techniques consisting of the lumped circuit, resonator, transmission line and free space methods (Chandrasekaran et al., 2013). A network analyzer with an open-ended coaxial probe, which is free space method, is normally used to measure the dielectric properties of foods (Regier et al., 2017b).

Adjusting dielectric properties of foods to cope with non-uniform temperature distribution

Non-uniform temperature distribution causes rapid heating of some food materials while other food materials are heated to a lower degree. Thus, non-uniform temperature distribution is considered a major problem in microwave heating (Chandrasekaran et al., 2013). To reduce this problem during microwave heating, methods have been proposed consisting of adjusting the dielectric properties of foods, incorporating hybrid conventional and microwave heating, controlling the food geometry, using suitable spacing and orientation of metallic bands to provide shielding, using a suitably designed microwave oven, handling the heating cycle and using reduced microwave power heating for longer durations (Vadivambal and Jayas, 2010).

With microwave pasteurization and sterilization of non-homogeneous foods, it is important to know which food component has the slowest heating rate and a model food is developed to represent that kind of food. A whey protein gel system can be formulated with chemical markers for non-enzymatic browning reaction to have similar dielectric properties to those of the slowest heating food. This gel can be heat-processed in the machine to identify the cold spots and hot spots of the food in the package (Tang, 2015).

Packaging of microwavable foods

Packaging of microwavable food products is important due to its impact on protecting the quality and safety of the packaged food, extending the shelf life of the food and providing uniform microwave heating of the food. Thus, suitable packaging selection, barrier design and package design are required (Schiffmann, 2017).

Packaging design

Packaging design mainly focuses on the shape and size, with general rules applying, as mentioned by Muthukumarappan and Swamy (2019). Design simplicity normally means the shape is oval or round to avoid edge heating. Rectangular container geometry, using a common non-microwave tray shape, is hottest at the corners, coolest in the center and near walls is slighter cooler than corners and consequently is not recommended (Vadivambal and Jayas, 2010). The thickness of the package is limited by the microwave frequency and depends on the product's weight and volume. A single layer is sufficient for cook-chilled foods with a short shelf life, but more layers with high protection are needed for long shelf life (Muthukumarappan and Swamy, 2019).

Packaging for sterilization using microwaves should be able to withstand high heat and pressure. The thickness of the package is also limited due to the penetration depth of microwaves inside the package. The package should prevent oxygen movement very well; therefore, many layers are designed for the expected shelf life. The packaging should not allow migration of substances to the food. The design of the package should provide uniformity in heating (Lingle, 2015; Schiffmann, 2017; Stanley and Petersen, 2017).

Packaging materials

Packaging materials for microwave foods must be selected carefully to meet important requirements. Paperboard containers (folded or press-molded) are used mostly for microwave food products in the USA because they provide a sturdy structure and the coating supplies chemical resistance and sealing ability. Soda-lime glass and borosilicate glass jars should not be used for microwavable products because they are easily breakable, have a high cost and shipping weight, and tend to get hot during heat transfer. Metal and aluminum are not suitable for microwavable food packaging because these materials will reflect microwaves back to the magnetron and cause undesirable arcing. Aluminum foil should not be used in the laminate structure in microwave processing, as it will prevent the microwaves from heating the food. Normally ethylene vinyl alcohol is used as an oxygen barrier. Lamination usually consists of different thicknesses of polypropylene, ethylene vinyl alcohol and polypropylene. The shelf life is normally 6–12 mth at room temperature. For a longer shelf life, more layers are needed (Lingle, 2015; Stanley and Petersen, 2017; Schiffmann, 2017).

Active containers

Active containers are a main category of microwave containers as they interact with the microwave field to facilitate other conditions besides holding or containing the food during microwave heating (Schiffmann, 2017). Generally, active containers are classified into three basic classes consisting of shields, susceptors and field modifiers. Shields prevent a food item from absorbing heat from the microwaves (Kanishka et al., 2013). Susceptors become hot and transfer heat to the surface of the microwaved-cooked food mainly by conduction. A field modifier plays a role in improving the distribution of the microwave energy (Schiffmann, 2017).

Microwave ovens

After World War II, Henry A. Boot and John T. Randal developed the magnetron that generates microwaves and subsequently, Percy L. Spencer developed domestic and industrial microwave ovens. Ongoing development has resulted in many types being currently available. The microwave oven is an appliance that heats and cooks food items quickly using microwaves, with the equipment being classified as either a multi-mode applicator or a single-mode applicator (Regier et al., 2017a).

Multi-mode applicator

The multi-mode applicator is the most popular applicator in microwave systems with a larger volume than a domestic microwave oven. There are many magnetrons with low power (800–1,200 W) above the cavities that transmit microwaves to the cavities. The energy from the microwaves is transmitted into the applicator with the support of the waveguide and passes through multiple reflections from the cavity walls. The food materials move along a Teflon conveyor belt or rotate on shelves. Normally, an oven with a multi-mode applicator uses magnetrons with 2,450 MHz frequency. Good engineering design is very important to provide good transfer of waves in the waveguide and to ensure an even wave distribution in the cavity and uniformity of heating in the food items (Regier et al., 2017a).

Single-mode applicator

The single-mode applicator contains only one magnetron with high power. The microwaves are generated and transferred through the waveguide. The food materials are transported along a Teflon conveyor belt or in a cylindrical Teflon or ceramic tube in a cylindrical cavity (Regier et al., 2017a).

Good engineering design is very important to produce good transfer of waves in the waveguide and even wave distribution in the cavity and uniformity of heating in food items. Microwave-assisted thermal sterilization (MATS) and microwave-assisted pasteurization (MAPS) systems use a single mode 915 MHz frequency (Tang, 2015).

Microwave types and components

Domestic microwave oven

Domestic microwave ovens are used commonly in households all over the world; however, an uneven electric field distribution in these microwave systems causes nonuniform heating of food items (Vadivambal and Jayas, 2010). A rotating plate or rotating wave stirrer can help to obtain better heating uniformity. The microwave oven consists of a high voltage transformer which transfers energy to the magnetron, a high voltage capacitor, a diode, a magnetron, a waveguide, a cavity or oven, a turntable and a stirrer or both and a controller. Normally, the door has a wire mesh (called a choke) to prevent microwave leakage (Law and Dowling, 2018).

Continuous microwave oven

There are two types of industrial continuous microwave ovens with one operating in single-mode and the other in multi-mode. In single mode, only one magnetron with high power is used. The magnetron sends the microwaves through the waveguide to the cavity. There is a protective device called a circulator to prevent the microwaves reflecting to the magnetron. The reflected waves are sent to the water load and the water absorbs the reflected waves. There is also a tuner for adjusting the waves mostly to the cavity for high efficiency. The food materials are transferred on a Teflon belt and heated in the cavity. There are chokes on both sides of the cavity to prevent microwave leakage (Ozcelik and Puschner, 2017).

In single mode applications such as the MATS system, the conveyor moves the ready-to-eat packages through the preheating, heating, holding and cooling sections. The belt speed can be varied using a variable motor controller. The 915 MHz magnetron with water cooling sends the microwaves through the waveguide and the waves are then separated into the top and bottom of the cavity and the waves propagate top-down and bottom-up on the packages. There are four modules, with each module uses different wattages. The packages are surrounded by water at controlled temperatures, such as preheating at 70°C, heating at 121°C, holding at 121°C and cooling at 20°C. Each section has a counter pressure to prevent bursting of the package and to prevent any water boiling. The process is fully automatic (Tang, 2015).

A multi-mode continuous microwave oven has many magnetrons at 2,450 MHz with low power (800–1,200 W). There are two magnetrons per module with four modules. The magnetron transfers the microwaves through the short waveguide down to the cavity in each module. The Teflon belt transfers the food samples through the cavity and the speed, and hence the cooking time, can be controlled. The power can be adjusted using the power controller (Auksornsri and Songsermpong, 2017; Pongpichaiudom and Songsermpong, 2018).

Combined microwave and infrared oven

A microwave oven combined with an infrared (IR) oven has been designed in the laboratory of Food Engineering Lab, Department of Food Science and Technology, Faculty of Agro-Industry, Kasetsart Univerisy, Bangkok,Thailand, which is a continuous process to improve microwave-baked products, puffing of pork rind, rice grains and paddy, rice crackers, shrimp crackers and drying of instant wheat noodles. The combination of microwave energy and IR heating can reduce the baking time and energy, can brown the products and yield good quality (Rungsee and Songsermpong, 2014).

Microwave vacuum oven

A microwave vacuum oven uses six magnetrons at 2,450 MHz in multimode operation. The trays revolve or can be designed as a revolving basket. The unit has a condenser and vacuum pump. Power controllers are used to control each magnetron (Kaensup et al., 2002)

In-tube continuous flow microwave pasteurizer and ultra-high temperature

In this system, the Teflon or ceramic tube is located at the center of the cylindrical cavity. Single mode is used with a magnetron of 915 MHz and high power. The liquid is pumped through the Teflon tube and the microwaves are directed around the cavity during the process. Basically, this microwave design focuses on the liquid along the center of the tube; therefore, the liquid is heated in a short time that is suitable for pasteurization and ultra-high temperature (UHT) treatment of liquid or particulate products (Coronel et al., 2006; Kumar et al., 2008; Steed et al., 2008).

Microwave processing technology for food safety and quality

Effect of microwave heating on inactivation of micro-organisms and enzymes

Inactivation of micro-organisms and enzymes using microwave processing is mainly due to thermal effects, involving the denaturation of enzymes, proteins and nucleic acids by heat from electromagnetic waves and food interaction. Enzymes act as catalysts for biochemical reactions in the living cells of micro-organisms; as proteins, their primary, secondary and tertiary structures are denatured when subjected to high temperature. Thus, the enzymes lose their active sites, reducing some biochemical activities essential for the survival of the microorganism. In addition, nucleic acids, typically DNA are also destroyed at high temperatures (Dev et al., 2012).

Besides thermal effects, the specific non-thermal effects have been investigated during microwave processing (Shamis et al., 2012). A non-thermal effect on the micro-organism and enzyme inactivation is mostly due to the electric field. For micro-organisms, non-thermal effects act on cell membranes integrity and intracellular protein release (Guo et al., 2020). When the electric magnitude is sufficiently high and the transmembrane potential is over a critical value, the dielectric breakdown of cell membrane occurs, leading to pore formation, higher permeability and eventually, irreversible loss of cell integrity (Kozempel et al., 2000; Zimmermann et al., 1994).

Generally, microwave exposure would not affect the primary structure of protein (Regier, 2017); however, in the system of an aqueous reaction, the microwave radiation excites the molecules to higher vibrational and rotational energies, leading to weakening of chemical bonds (Wang and Wang, 2016). In addition, the interaction between the protein in the polar group and the oscillating electric fields influence secondary and tertiary structural modifications, resulting in damaged functionality (Guo et al., 2020). Damm et al. (2012) noticed that the tertiary structure of both proteins and enzymes might only be affected by an electric field of 1×10^8 V/m.

Effect of microwave heating on nutrition and sensory quality

Microwave heating is normally a high-temperature, short-time process that improves the nutrition and sensory quality of the final products (Contreras et al., 2017). This is the result of internal heat generation and volumetric heating in the microwave heating system. Compared to cooked products using traditional methods, the qualities of microwavable food products are better due to faster heating and high energy efficiency. Consumers preferred microwave pasteurized kiwifruit puree to that processed using a conventional treatment, since the microwaves did not change the sweetness, acidity and sensory attributes of appearance, odor, taste and overall likeability (Benlloch-Tinoco et al., 2013). Microwave-vacuum drying is recommended for vegetable products to prevent loss of flavor, nutrients and functional properties and to retain antioxidant content, antioxidant activity and the bioavailability of antioxidants, because of the rapid heating rate and removal of oxygen (Podsędek, 2007). The quality characteristics of frozen beef subjected to conventional and microwave thawing were more acceptable to panelists and had lower drip loss; thus, microwave thawing was suggested as the preferred method for thawing to minimize deterioration (Kim et al., 2013). With foods containing high nutrient levels, such as meat and fish, microwave cooking and roasting reduce vitamin loss as vitamins are heat-sensitive and the essential nutrient composition is maintained (Contreras et al., 2017). Microwave drying of crickets was compared with steam blanching and then hot-air drying; the results showed that microwave-dried crickets had greater mineral content, better color, lower microbiological loads and more vitamin B2 than those subjected to conventional drying (Bawa et al., 2020). The pasteurization of milk using a microwave pasteurizer, compared to heating in a hot water pasteurizer, produced similar results and in particular, no difference in quality (Albert et al., 2009).

Temperature measurements of foods in microwave systems

Generally, temperature distributions in microwaved food products are measured using shielded thermocouples, fiber optic sensors, wireless sensors, infrared thermography, microwave radiometry and magnetic resonance imaging (Muthukumarappan and Swamy, 2019).

Shielded thermocouples

Regular thermocouples cannot be used in a microwave oven because these probes are made from metallic wires that disturb magnetic fields, leading to overheating, arcing and damage to the instrument and sample (Muthukumarappan and Swamy, 2019). Shielded thermocouples with nickel-coated copper braid in an aluminum tube can be used in the microwave oven to measure with a variability of 1°C (Ramaswamy et al., 1998).

Fiber-optic temperature sensor

A fiber-optic temperature sensor can be used in a microwave oven to obtain high accuracy and it does not interfere with electromagnetic fields (Muthukumarappan and Swamy, 2019; Durka et al., 2010); it has been used in research and development and microwave heating systems.

Wireless sensor

A wireless sensor is considered an attractive device because it is contactless and has low power consumption (Chen et al., 2018). There are three types of wireless, passive, *in-situ* sensors: based on surface acoustic waves, inductive coupled and microwave-based (Nyfors, 2000; Cheng, 2014). Normally, microwave-based sensors are more advantageous due to their high quality, simpler configuration and multi-parameter measurement capability. A microwave wireless, passive sensor operates based on the microwave backscattering phenomenon. The sensor is combined with a sensing unit (microwave resonator, filter or Complementary Metal Oxide Semiconductor [CMOS] devices) fitted with an antenna (Chen et al., 2018). The sensor can be dipped in the food system to conduct the heat penetration study at the coldest spot in ready-to-eat foods in hermetic containers (Tang, 2015).

Infrared thermography

Infrared thermography is a good measuring method for surface temperature and has good spatial resolution. Infrared sensors show the exact surface temperature within the sensor's field of view with a decent time resolution. However, infrared sensors are metallic and cannot be located inside a microwave electromagnetic field. In addition, measurements must be performed through a shielded window because of the sensitive electronics inside the infrared sensors that require extensive electromagnetic shielding to allow accurate measurements when electromagnetic fields are active (Muthukumarappan and Swamy, 2019).

Microwave radiometry

In microwave radiometry, the thermal energy is identified and used as a source for temperature assessment in the microwave frequency range. Compared to the infrared frequency range, the penetration depth of the radiation in a microwave is higher and can sense the temperature up to 7 cm below the surface. However, the spatial resolution of this method is lower than for infrared thermography due to using longer wavelengths (Muthukumarappan and Swamy, 2019).

Magnetic resonance imaging

Magnetic resonance imaging is used to measure three-dimensional temperature distribution and can be done offline after heating and online for design purposes in the microwave systems. The probe does not need to be combined with the sample and the sample does not have to be broken up to get subsurface temperature measurements information. This method provides good spatial resolution; however, magnetic resonance imaging tomography is very expensive (Muthukumarappan and Swamy, 2019).

Microwave processing applications

One of the techniques with widest application in food processing is microwave technology, which has been shown to be more advantages than conventional technology. A summary of recent applications of microwave applications for food safety and quality is shown in Table 2.

Table 2 Examples of microwave (MW) processing applications for food safety and quality

Material	Microwave processing	Results	Reference
In-packaged jasmine cooked rice	MW pasteurization (eight units at 800 W and 2,450 MHz)	5 log reduction of *Listeria monocytogenes*. Good color, texture and sensory for 30 d at 8°C.	Auksornsri and Songsermpong (2017)
Fried rice	MAPS system	Extension of shelf-life to 6 wk at 7°C.	Montero et al. (2020)
Carrot slices	MW pasteurization (200 W, 400 W or 600 W)	Reduction of pathogens up to 90% at 600 W.	Roohi and Hashemi (2020)
Chicken breast	MATS system	Increased sensory acceptability.	Tang (2015)
Red pepper (*Capsicum annuum* L.)	MW-IR sterilization	Log reduction of 8.85 of total plate count (*S. Typhimurium*) and 7.73 log reduction of yeast and mold (*A. flavus*).	Shirkole et al. (2020)
Frozen hami melon	Domestic MW thawing	Reduction of drip loss, texture damage and discoloration. Retention of ascorbic acid.	Wen et al. (2015)

Table 2 Continued

Material	Microwave processing	Results	Reference
Surimi slabs	Continuous MW thawing	Reduction of the edge heating of smaller-sized sample and uniform heating of larger-sized sample.	Zhang et al. (2019)
Yellow sweet pepper	MW drying (0.35 W/g, 0.70 W/g 1.05 W/g or 1.4 W/g)	Improvements in color parameters, browning index, total carotenoid, and sensory score.	Swain et al. (2014)
Instant noodles; Instant rice	MW drying	Reduction of rehydration time to 3 min in hot water (90°C)	Pongpichaiudom and Songsermpong (2018); Phukasmas and Songsermpong (2019).
Dried paddy	MW drying	Accelerated aging for 2–3 mth.	Le et al. (2014)
Rice bran	Continuous MW drying	Prevention of hydrolytic reaction and oxidative rancidity up to 16 wk.	Pongrat and Songsermpong (2019)
Cricket's power	MW drying (600 W, 720 W or 840 W)	Higher vitamin B2 content, mineral element, color and microbiological properties	Bawa et al. (2020)
Mint leaves	MW vacuum drying (8.0 W/g, 9.6 W/g or 11.2 W/g and 13.33 kPa and 2,450 MHz)	Reduction of drying time by 85–90%. Retention of sample color. More porous and uniform sample.	Therdthai and Zhou (2009)
Barley	MW freeze drying	Reduction in energy consumption and drying time. Preservation of chlorophyll and flavonoids.	Cao et al. (2018)
Raspberry puree foam	MW freeze drying	Retention of ascorbic acid and anthocyanin and foam.	Ozcelik et al. (2020)
Longan flesh	MW/hot-air drying	Reduction of drying time and energy consumption	Varith et al. (2007)
Fresh *Moringa oleifera* pods	MW/hot-air drying (50°C, 60°C or 70°C with 1 W/g)	Preservation of volatile compound and bioactive molecules.	Dev et al. (2012)
Paddy rice	MW fluidized-bed drying	Good quality of product.	Sangdao et al. (2010)
Celery	MW fluidized-bed drying (45°C, 55°C or 65°C with 0 W/g, 1 W/g or 2 W/g)	Reduction in microwave energy greater than 50%.	Kaur et al. (2018)
Parboiled wheat	MW spouted bed drying	Reduction of drying time to 60% and 85 % at 3.5 W/g and 7.5 W/g, respectively, and high diffusivity value.	Kahyaoglu et al. (2012)
Shrimp cassava cracker,	MW puffing (1,200 W for 1 min)	High volume expansion and texture	Nguyen et al. (2013)
pork rind	MW puffing (1,200 W for 3 min)	Higher sensory evaluation score.	Truong et al. (2014)
Paddies and agglomerated rice	Domestic MW puffing	Improvement of product quality.	Chanlat and Songsermpong (2013); Mom et al. (2020)
Peanut	MW blanching	Retention of flavor and reduced time and energy.	Schirack et al. (2006
Rice bran	MW blanching	Extension of shelf-life to more than 4 mth at 4°C.	Pongrat and Songsermpong (2019)
Potato chip	MW frying	Reduction in oil content. Retain crispiness and natural color.	Su et al. (2016)
Green tea leaves	MW extraction	Reduction in extraction time for polyphenol and caffein.	Pan et al. (2003)
Mango peel	MW extraction (700 W for 3 min)	High pectin yield of 13.85%. Increased porosity.	Wongkaew et al. (2020)
Potato pulp	Continuous flow MW extraction	Higher pectin yield of 40–45%.	Arrutia et al. (2020)
Rice flour bread	MW baking	Reductions in glycemic index and baking time.	Therdthai et al. (2016)

MAPS = microwave-assisted pasteurization; MATS = microwave-assisted thermal sterilization

Microwave-assisted pasteurization and sterilization of ready-to-eat foods in hermetic containers

Pasteurization is a technique using mild heat to destroy pathogens and spoilage microorganisms and some enzymes, resulting in enhanced food safety and shelf-life (Chandrasekaran et al., 2013). Sterilization uses a high temperature to destroy the spores of important microorganisms to render a product free of microorganisms that can grow in the product under non-refrigerated conditions (Nott and Hall, 1999). Post-packaging pasteurization and sterilization technology, involving both microwave pasteurization and sterilization have been developed for food preservation with high quality and extended shelf life (Tang, 2015).

Microwave-assisted pasteurization

Microwave-assisted pasteurization destroys pathogenic microbes and some enzymes using microwaves at a sublethal temperature. The mechanisms of this process can be selective heating, electroporation, cell membrane rupture or magnetic field coupling (Kozempel et al., 1998). With selective heating, the temperature in the product subjected to the microwaves is higher than that of surrounding fluid, causing the microorganisms to be destroyed quickly. According to electroporation theory, the cellular materials leak due to the electrical field across the cell membranes of the pores. Cell membrane rupture occurs when the voltage applied cracks the cell membrane. An alternative approach is based on the coupling of electromagnetic energy with protein or DNA that disrupts the internal cell components (Kozempel et al., 1998). In a study on continuous microwave pasteurization of in-packaged jasmine cooked rice, the samples were packed in a polypropylene plastic cup and sealed with a lidding film and then pasteurized in a continuous microwave system. The product was compared with that produced using a conventional steamer. The results indicated that the sample following microwave treatment (eight units at 800 W and 2,450 MHz) had a similar 5 log reduction for control of *Listeria monocytogenes*. The microwave pasteurization maintained a low microorganism count and good color, texture and sensory attributes for 30 d of storage at 8°C, while the shelf life of the conventional process was less than 7 d, with the improvement due to microwave pasteurization using UHT, a short time and rapid cooling (Auksornsri and Songsermpong, 2017). A MAPS system applied to fried rice, extended the shelf life from 5 d to 6 wk at 7°C with very high sensory scores that were much better than for the control (Montero et al., 2020). Carrot slices were pasteurized using microwaves at 200 W, 400 W or 600 W for up to 250 s after pretreatment with air drying at 25°C for 3 hr, with the highest reduction level of pathogens of about 90% being noticed at 600 W of power (Roohi and Hashemi, 2020)

Microwave-assisted sterilization

Microwave-assisted sterilization is based on the pH value of the food products because the pH is related to the thermal resistance of bacterial spore formers. For example, High acid foods with pH ≤ 4.6 can be treated at 80–90°C for some period. Low acid food products at pH > 4.6 are subjected to a temperature of about 121°C for some period to achieve commercial sterility (Bozkurt-Cekmer and Davidson, 2017). Microwave-assisted thermal sterilization (MATS) of in-packaged, ready-to-eat meals has been approved by the US Food and Drug Administration (Chandrasekaran et al., 2013). The first product was mashed potato as a homogeneous food sample. The second product was salmon in alfredo sauce as a non-homogeneous sample. The third product was chicken and dumplings in pouches. The food quality from MATS processing was much better than from a conventional steam process, as the former process had similar cooking values at hot spots and cold spots, while in the steam retort, the cooking values at hot spots and cold spots were very different (Tang, 2015). The MATS processing also has been used for the medium moisture food, such as cooked rice (Auksornsri et al., 2018). The chicken breast sterilized by MATS had overall acceptability and flavor (6.7 score) that was higher than from retorting (5.5 score). The same trend was shown in chicken and dumpling. Some of the products also had higher scores than frozen foods (Tang, 2015). Red pepper (*Capsicum annuum* L.) was sterilized using microwave by short time intensive microwave-infrared (MW-IR) radiation for 15 s, 30 s, 45 s, 60 s or 75 s, resulting in about an 8.85 log reduction in the total plate count (*S. Typhimurium)* and a 7.73 log reduction in the yeast and mold count (*A. flavus*) compared to natural microbial flora (Shirkole et al., 2020)

Other systems in Europe

All microwave pasteurization and sterilization systems in Europe use multi-mode and 2,450 MHz frequency and have been in operation for the last 30 yr. The Nutripack system from France uses a valve system attached to the lidding film to prevent the lid bursting and the valve allows steam to exit, which removes any oxygen and air in the headspace. The Micvac system from Sweden also uses a valve system attached to the lidding film and the manufacturers claim that the pasteurized product can be stored at refrigerator temperature for at least 30 d. The Berstoff system from Germany and the

OMAC system from Italy were developed for the microwave pasteurization of ready-to-eat foods. Tops Foods from Belgium developed microwave pasteurization and sterilization, with pasteurized products able to be kept at refrigerator temperature for 35 d and sterilized products can be kept for 1 y at room temperature, while, in addition, they can sterilize two sections needing different heating regimes in the one package (Tang, 2015; Stanley and Petersen, 2017).

Microwave-assisted in-tube pasteurization and ultra-high temperature treatment

The continuous flow microwave pasteurization and UHT system for liquids and particulates was developed by Industrial Microwave Systems, USA. The company used the 915 MHz frequency and single mode. For milk and high protein liquids, no fouling occurred and the processing time was brief compared to traditional steam heating. The system generated greater production along with better quality, with minimal color, sensory and nutritional changes. A study of scaling-up the equipment from 5 kW to 60 kW was done and testing with UHT treatment of green peas and carrot puree produced good results (Kumar et al., 2008). The process was used for pasteurization and UHT treatment of low acid and acid products and further scaling-up to 100 kW and commercial production have been reported (Coronel et al., 2006; Kumar et al., 2008; Steed et al., 2008).

Microwave-assisted thawing and tempering

Microwave-assisted thawing is the fastest method for thawing frozen food products, such as frozen meat, fish, vegetables, fruit, butter or juice concentrate. The electromagnetic waves are directed toward the sample through a waveguide with the absence of conductors or electrodes. In contrast, in a conventional thawing and tempering system, the heat is supplied to the surface of materials and transferred to the center of those materials by conduction (James et al., 2017).

Microwave-assisted tempering with power was provided using a 30 kW magnetron and 896 MHz, in which the microwaves moved into the chamber via waveguides sited at the top and bottom. Rotating metal discs were placed above and below the product to supply a uniform microwave field and the loaded pallet was subjected to 90 mm cyclic movements during tempering of the meat blocks (James and Crow, 1986).

Domestic microwave thawing and tempering

Normally, a defrost control system uses 10% of the original microwave power. In a conventional thawing system, the thawing time might be predicted by limited different technologies with good accuracy based on the type of food. Modeling of microwave-assisted thawing and tempering have been used and verified such as for thawing meat blocks, beef quarters and pork legs, under a wide range condition (James and James, 2002). Wen et al. (2015) applied various thawing conditions of air, immersion, microwave and high-pressure at 2 × 2 × 2 cm in frozen hami melon. The results indicated that the drip loss, texture damage and discoloration of the microwave thawing treatment were less than from using other treatments. In addition, the retention of ascorbic acid was maximized using microwave-oven thawing to treat strawberries (Holzwarth et al., 2012).

Continuous microwave thawing and tempering

Single-mode and multi-mode continuous microwave ovens can be used. The power should be as low as possible and the temperature should be below freezing, normally at -1 to -2°C. More than 200 commercial industrial microwave ovens have been used to temper frozen blocks of foods (James et al., 2017). Zhang et al. (2019) investigated the heating characteristic of continuous 915 MHz pilot scale microwave thawing. It was noticed that in the thawing system the operating frequency changed with the time and was affected by the loading. In addition, the local temperature was ranged greatly with different frequency settings and various concentration of microwave energy. The results showed that the smaller the sample distance of the surimi slabs, the less edge heating; furthermore, larger-sized samples produced more uniform heating in the direction of movement.

Microwave-assisted drying

Microwave-assisted drying is applied in food products with the advantage of achieving rapid drying rates and improving the quality of food. The microwave energy absorption level is based on the moisture content in the products. Due to volumetric heating in microwave drying, vapor is produced inside, resulting in an internal pressure gradient that forces the water from the product (Chandrasekaran et al., 2013). Swain et al. (2014) studied yellow sweet peppers (*Capsicum annum* L.) that were dried using microwave-assisted drying at 0.35 W/g, 0.70 W/g, 1.05 W/g or 1.4 W/g and at air temperatures of 30°C, 45°C and 60°C, with an air velocity of 1.5 m/s. The microwave system strongly affected the color parameters, browning index and total carotenoid and sensory scores of the sample.

Microwave-assisted atmospheric drying

Microwave drying of instant noodles was investigated in the laboratory of Food Engineering Lab., Department of Food Science and Technology, Faculty of Agro-Industry, Kasetsart University, Bangkok, Thailand. The results showed that microwaving could rehydrate the noodles in 3 min using hot water at 90°C and protein-enriched instant noodles could also rehydrate in the same time (Pongpichaiudom and Songsermpong, 2018). In addition, instant rice was developed and could rehydrate after boiling in water for 3 min (Phukasmas and Songsermpong, 2019), while instant fermented rice noodles were developed and patented that could rehydrate in boiling water after 3 min (Songsermpong et al., 2016). The paddy was dried using a continuous microwave oven and the rice showed accelerated aging for about 2–3 mth (Le et al., 2014). Pongrat and Songsermpong (2019) researched the stabilization of rice bran using a continuous microwave oven. Their results indicated that the hydrolytic reaction and oxidative rancidity of the sample could be prevented so that the product could be stored for up to 16 wk. Cricket powder was produced using microwaves at 600 W, 720 W or 840 W power levels by Bawa et al. (2020). It was found that the vitamin B2 content in the microwave treatment was higher than for a hot-air oven; furthermore, the mineral elements, color and microbiological properties were improved using the microwave drying technique.

Microwave-assisted vacuum drying

Microwave-assisted vacuum drying is the combination of vacuum drying and microwave heating in pulses that can improve its thermal efficiency (Zhang et al., 2006). Vacuum drying is a technique for foodstuff drying at reduced pressures causing water to become vapor at a low boiling point. Microwave heating transmits energy due to volumetric heating that can remove water rapidly. The product will have very good color, good quality and nutrition, since very little oxygen is in the chamber and the temperature is in the range 40–50°C. Mint leaves were dried using microwave vacuum drying with microwave power intensities of 8.0 W/g, 9.6 W/g or 11.2 W/g at a pressure of 13.33 kPa and a frequency of 2,450 MHz for 15 min and compared to leaves subjected to hot-air drying at 60°C or 70°C for 120 min. Microwave vacuum drying reduced the drying time by 85–90% and the color parameters were superior to those of leaves processed using hot-air drying. In addition, the structure of the leaves dried using microwave vacuum drying was more porous and uniform than for the hot-air-dried leaves. Clearly, the rehydration rate constants of the dried samples from microwave vacuum drying at 9.6 W/g or 11.2 W/g were higher than that of the hot air-drying technique (Therdthai and Zhou, 2009). Many kinds of puffed fruits and vegetables can be processed using this microwave vacuum drying technique, such as mango slices (Pu and Sun, 2015) and durian slices (Bai-Ngew et al., 2011).

Microwave-assisted freeze drying

Microwave-assisted freeze drying is considered the most advantageous technique for heat-sensitive foods and pharmaceutical and biological materials (Zhang et al., 2006) due to the very low temperature in the frozen state, the use of very low pressure with no oxygen and the direct sublimation of the ice to vapor. Compared to conventional drying technology and microwave vacuum technology, freeze-dried products have the best quality, though it is the most expensive of the three processes. Microwave freeze drying (MFD) was better than freeze drying (FD) for drying barley grass because MFD could decrease the energy consumption by 42% and the drying time by 43%; in addition, the remaining chlorophyll and flavonoids contents in the barley grass were greater using MFD (Cao et al., 2018). Raspberry puree foam was dried using freeze drying and microwave-assisted freeze drying, then stored at 37°C for 12 wk in a vacuum package. The storage stability (retention of ascorbic acid and anthocyanin, and foam) of samples treated using microwave-assisted freeze drying was better compared to those dried using freeze drying (Ozcelik et al., 2020).

Microwave-assisted hot-air drying

Microwave-assisted hot-air drying combines hot air with microwave heating in three stages. In the first stage, microwave heating is applied at the beginning of the hydration process. The second stage involves a rapid drying period, with a stable temperature profile being set up to expel vapor from the product, forming porous structures called puffing. In the final stage, the moisture content at the center of the product is stabilized by removing bound water (Zhang et al., 2006). Microwave-assisted hot-air drying (MAHD) of longan flesh was studied based on a stepwise process to achieve maximum drying efficiency using 40°C hot air with 450 W microwave power for 1.7 hr and then 60°C hot air with 300 W microwave power for 3.3 hr, compared to 60°C hot-air drying. The drying time reduction was 54.3% and specific energy consumption reduction was 48.2% (Varith et al., 2007). MAHD was used to dehydrate fresh *Moringa oleifera* pods at 50°C, 60 °C or 70°C using 1 W/g of power density. The results indicated that the loss of volatile compounds was significantly lower than for the hot-air dried samples and the bioactive molecules were preserved mostly due to the faster drying time (Dev et al., 2012).

Microwave-assisted fluidized-bed drying

During fluidized-bed drying, the solid particles are forced to lift in the air stream, high rates of heat and mass transfer take place between the air and solid phases. Therefore, microwave-assisted fluidized-bed drying is used for drying moist, granular materials (Ranjbaran and Zare, 2013). A continuous fluidized-bed microwave paddy drying system was developed that had microwave leakage lower than the safety standard, while maintaining the quality of the paddy; thus, this system was considered promising for paddy drying (Sangdao et al., 2010). The drying kinetics were studied of celery using a microwave assisted fluidized-bed dryer at 45°C, 55°C or 65°C with 0 W/g, 1 W/g and 2 W/g, respectively. It was shown that the model at 55°C and 1 W/g was the best for moisture ratio prediction and the microwave energy reduced the drying time by more than 50% (Kaur et al., 2018).

Microwave-assisted spouted-bed drying

Spouted-bed drying is a modified method of a conventional fluidization technique that facilitates agitation of relatively coarse particles on the drying bed and this facilitates heat and mass transfer caused by the constant renewal of the boundary layer at the particle surface. The combination of microwaves and spouted-bed drying produces better textural properties of products and decreases the processing time (Feng et al. 2012). Compared to the spouted-bed technique alone, microwave-assisted spouted-bed drying of parboiled wheat reduced the drying time to 60% and 85% at microwave power intensities of 3.5 W/g and 7.5 W/g, respectively. In addition, the effective diffusivity values in this process were higher (5.06×10^{-10}–11.3×10^{-10} m^2/s) while that of spouted-bed drying were in the range 1.44×10^{-10}–3.32×10^{-10} m^2/s (Kahyaoglu et al., 2012).

Microwave-assisted puffing

Microwave-assisted puffing has been recommended for low-fat products to replace deep-fried food products (McAlister, 1972; Schwab et al., 1994). During microwave puffing, the material undergoes substantial structural changes and moisture loss. This process involves the complex physical phenomena of electromagnetic heating, heat and moisture transport, puffing, evaporation and large levels of deformation (Rakesh and Datta, 2011). Shrimp cassava cracker was developed by applying microwave puffing at 1,200 W for 1 min. The resulting texture of the puffed microwave shrimp cracker was harder than for oil-fried cracker, whereas the volume expansion was less than that of oil frying. This might be explained by the formation of air bubbles inside the fried cracker caused by long frying and high temperature that create a more porous structure (Nguyen et al., 2013). Puffed pork rind using microwave cooking was developed using 1,200 W for 3 min and compared with fried pork rind. After treatment, the sensory evaluation produced higher scores for flavor, crispness and hardness of the puffed sample than for the fried sample, due to the oil content from frying contributing to softness in the samples. The consumers preferred the puffed pork rind product more than the fried one (Truong et al., 2014). Puffed paddy and puffed agglomerated rice (khao tan) cooked in a domestic microwave oven were developed with good quality (Chanlat and Songsermpong, 2013; Mom et al., 2020).

Microwave-assisted blanching

Blanching is a pretreatment to maintain the qualities of food through the inactivation of enzymes and a reduction in the volumetric material by removing the trapped air in intracellular spaces and reducing the microbial load and undesirable color, odor and flavor (Binsi et al., 2014). Traditional blanching methods use steam or hot water, but microwave blanching applies high temperature for a short period using volumetric heating (Muthukumarappan and Swamy, 2019). Microwave blanching and traditional blanching of peanuts were studied by Schirack et al. (2006). It was noticed that microwave blanching with high temperature led to better flavor and savings in energy and time. The stabilization of rice bran using continuous microwave oven heating was achieved by adjusting the moisture content of the bran to 21% (wet basis) and then heating in a microwave tunnel at 6,400 W and 2,450 MHz for 15 min 45 s before packing in zipper-top bags. The shelf life at 4°C could be extended from 1 d to 4 mth (Pongrat and Songsermpong, 2019).

Microwave-assisted frying

Frying is a process to provide specific sensory qualities of products, including taste, texture and color (Pankaj and Keener, 2017). Microwave application in a frying system will decrease the processing time, change the internal pressure of the product rapidly and maintain the oil quality (Muthukumarappan and Swamy, 2019). Microwave vacuum frying (MVF) and vacuum frying (VF) techniques were compared for cooking potato chips. After the treatments, MVF significantly reduced the oil content in samples from 39.14 to 29.35 g oil/100 g (dry basis) increased the crispiness and retained the natural color (Su et al., 2016). Modeling of the mass transfer of water and oil during microwave frying of frozen potato chips has been investigated (Poparisut and Songsermpong, 2010).

Microwave-assisted extraction

Microwave-assisted extraction is a method to increase the extracted bioactive compounds. A solvent is used for compound extraction from a sample placed in the microwave zone where the biomolecules and solvent align with the alternating microwave fields (Muthukumarappan and Swamy, 2019). Microwave-assisted extraction (MAE) was used to extract polyphenol and caffeine from green tea leaves. The results indicated that the extracted contents of polyphenol and caffeine from MAE (after 4 min) were higher than obtained at room temperature (after 20 hr), using ultrasonic extraction (after 90 min) and heat reflux extraction (after 45 min); in addition, using microwave-assisted extraction reduced the extraction time and was less labor intensive (Pan et al., 2003). The extractable yield of pectin was 13.85% from mango peel using microwave-assisted extraction at 700 W for 3 min and the product had greater porosity compared to the conventional method (Wongkaew et al., 2020). A continuous-flow microwave system was designed to extract the pectin from potato pulp by Arrutia et al. (2020) using 2,450MHz, and 400 W or 800 W for 5–60 min under constant stirring at 600 revolutions per minute. The yield of pectin after extraction was 40–45% that was more than twice that from using water extraction.

Microwave-assisted baking

Conventional baking involves heating using convection and conduction. In microwave-assisted baking, the microwaves interact with charged particles and polar molecules, resulting in rapid heating in the food material (Yolacaner et al., 2017). Microwave-assisted baking had a positive impact on rice flour bread quality by reducing the glycemic index to 61.67 compared to 80.24 of hot-air baking; furthermore, the baking time was reduced from 30 min to 12 min using microwaves during baking (Therdthai et al., 2016). Baking using microwaves together with infrared heating reduced the baking time and energy and produced a better-quality product compared to microwave baking alone (Rungsee and Songsermpong, 2014).

Concluding remark and future trends

Microwaves are not only commonly used in household devices everyday but have also been applied in industrial processing for several years. Based on this review, microwave food processing technology has clearly been successfully applied for food safety, quality and innovation in various food products using various processes. Over the next decade, microwave technology is expected to become even more popular, especially in developing countries. However, investigation is needed into improved machine design, scaling-up and process engineering, and the transfer of technology. The benefit of using microwave technology should be taught in more depth at the university level, as well as applied in the food industry to enhance knowledge, experience, innovation and technology development. The increased knowledge of the benefits should boost the further development of this technology.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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