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Review

Microwave food processing—A review

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ABSTRACT

Microwave heating has vast applications in the field of food processing such as cooking, drying, pasteurization and preservation of food materials. In this article, various applications of microwave food processing such as microwave cooking, microwave pasteurization and microwave assisted drying were extensively reviewed. The advantages and the factors affecting the microwave cooking of food materials have been reviewed. Microwave pasteurization of fresh juices, milk and various food products has been elaborately discussed. Microwave pasteurization has the ability to achieve destruction of microorganisms at temperatures lesser than that of conventional pasteurization due to significant enhancement or magnification of thermal effects. Applications of microwave drying include microwave assisted hot air drying, microwave vacuum drying and microwave freeze drying. Microwave drying combined with other conventional methods of drying enhances the drying characteristics of the sole effect of microwave drying. Modeling of microwave heating of food materials based on Maxwell's equations and Lambert's law equations have been reviewed along with their applications. Microwave modeling can be used to predict the temperature and moisture distributions during microwave heating of food materials. The factors affecting the dielectric property of food material and the applications of dielectric property measurements were also discussed. Various solution strategies to overcome non-uniform temperature distribution during microwave heating of food materials were proposed. It is required to obtain better end product qualities of food materials by conducting more research at pilot scale levels. It is also necessary to eliminate hot spots or non-uniform temperature distribution during microwave heating of food materials.

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1. Introduction

Microwave heating has vast applications in the field of food processing over a period of several decades. The applications of microwave heating in food processing include drying, pasteurization, sterilization, thawing, tempering, baking of food materials etc. (Gupta & Wong, 2007; Metaxas & Meredith, 1983). Microwave heating has gained popularity in food processing due to its ability to achieve high heating rates, significant reduction in cooking time, more uniform heating, safe handling, ease of operation and low maintenance (Salazar-Gonzalez, San Martin-Gonzalez, Lopez-Malo, & Sosa-Morales, 2012; Zhang, Tang, Mujumdar, & Wang, 2006). Moreover, microwave heating might change flavor and nutritional qualities of food in a lesser extent as opposed to conventional heating during cooking or reheating process (Vadivambal & Jayas, 2010).

Microwaves are electromagnetic waves whose frequency varies within 300 MHz to 300 GHz. Domestic microwave appliances operate generally at a frequency of 2.45 GHz, while industrial microwave systems operate at frequencies of 915 MHz and 2.45 GHz (Datta & Anantheswaran, 2000). This review article is divided into the following sections: Section 2, dielectric properties of the food materials, its measurement techniques and applications; Section 3, microwave cooking; Section 4, microwave drying; Section 5, microwave pasteurization and sterilization and Section 6, modeling of microwave–food interactions. This review focuses on the latest developments and the current status of research on microwave food processing and outlines the directions for future research.

1.1. Microwave heating mechanism

Microwave heating is caused by the ability of the materials to absorb microwave energy and convert it into heat. Microwave heating of food materials mainly occurs due to dipolar and ionic mechanisms. The presence of moisture or water causes dielectric heating due to the dipolar nature of water. When an oscillating electric field is incident on the water molecules, the permanently polarized dipolar molecules try to realign in the direction of the electric field. Due to the high frequency the electric field, this realignment occurs at a million times per second and causes internal friction of molecules resulting in the volumetric heating of the material. Microwave heating might also occur due to the oscillatory migration of ions in the food which generates heat in the presence of a high frequency oscillating electric field (Datta & Davidson, 2000). There are many factors which affect microwave heating and its heat distribution and the most important of them are the dielectric properties and penetration depth.

2. Dielectric properties

The ability of a material to convert microwave energy to heat can be understood by knowing its dielectric properties. The real part of dielectric property, termed as dielectric constant, signifies the ability to store electric energy and the imaginary part of dielectric property, termed as dielectric loss, signifies the ability to convert electric energy into heat,

$$\varepsilon^* = \varepsilon' - j\varepsilon'', \tag{1}$$

where ε ' and ε " are dielectric constant and dielectric loss respectively and $j = \sqrt{-1}$. The ratio of dielectric loss to dielectric constant is given by loss tangent and is expressed as,

$$\tan\,\delta = \frac{\kappa''}{\kappa'} = \frac{\varepsilon''}{\varepsilon'} \tag{2}$$

where κ' and κ" are relative dielectric constant and relative dielectric loss respectively, which are given as $\kappa' = \varepsilon' / \varepsilon_0$ and $\kappa'' = \varepsilon'' / \varepsilon_0$. Here, ε_0 is the permittivity of free space ($\varepsilon_0 = 8.854 \times 10^{-12} F/m$). The dielectric properties are mainly affected by the operating temperature and the microwave frequency used. Based on the microwave absorption, materials are classified into (i) absorbers or high dielectric loss materials which are strong absorbers of microwave (ii) transparent or low dielectric loss materials where microwave energy passes through the material with little attenuation and (iii) opaque or conductors which reflect the microwaves. Hence, a knowledge of dielectric properties is necessary to differentiate the materials into the above three categories.

The power penetration depth (D_p) is defined as the distance at which the power density drops to a value of $1/e$ from its value at the surface and is expressed as (Metaxas & Meredith, 1983),

$$D_p = \frac{c}{\sqrt{2}\pi f \left[\kappa' \left\{ \sqrt{1 + \left({}^{\kappa''}/_{\kappa'}\right)^2} - 1 \right\}\right]^{1/2}} \tag{3}$$

where c is the velocity of light given as $c = (\mu_0 \varepsilon_0)^{-1/2}$, ω is the angular frequency and μ_0 is the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ H/m). Eq. (3) is applicable for food materials which are non-magnetic ($\mu_r = 1$) in nature. The power which varies with the square of the electric field is given as,

$$q = \frac{1}{2}\omega\varepsilon_0\kappa''|\boldsymbol{E}|^2 \tag{4}$$

where **E** is the electric field intensity. Apart from the dielectric properties and the penetration depth, other factors which affect microwave food processing are microwave oven design (oven size and geometry), microwave frequency, placement of food material inside the oven, moisture content, density, composition, load, shape and the size of food materials (Icier & Baysal, 2004a). In general, the amount of moisture or water content in a food material plays a deciding factor in determining the dielectric properties of the food material, since water is a good absorber of microwaves.

2.1. Factors affecting dielectric properties of food materials

Microwaves are not absorbed by the material due to its electronic or atomic polarization, however, they might be absorbed owing to its dipole or ionic polarization. Dipole polarization is significant at frequencies above 1 GHz while ionic losses are predominant at frequencies below 1 GHz (Ryynanen, 1995). The dielectric constant of pure water decreases slightly with frequency. Similarly, the dielectric loss increases with increasing frequency for moist foods. The dielectric properties of food materials are mainly determined by their chemical composition and to a lesser extent of physical structure. Generally, food material consists of a mixture of organic material, water and salt. The dielectric loss at a particular frequency increases with the addition of salt. Salt solutions act as conductors in the presence of the electromagnetic field, hence a decrease in the permittivity and an increase in the dielectric loss factor were observed by Icier and Baysal (2004a). The dielectric property of water varies depending on whether it is in free or bound state. In the presence of an electric field, the polar molecules of water in free state orient more freely than those of bound water. For high water content frozen materials, the dielectric properties might increase with an increase in temperature in the melting zone. During runaway heating of frozen and thawed foods, the warm part gets rapidly heated and at the same time there are still some ice left in the food material and hence poses non-uniformity issues (Ryynanen, 1995). The dielectric characteristics of the food materials may also vary with their particle size, structure and density of the material. Dielectric properties are also affected by the apparent density of the air–particle mixture of a granular or particulate material (Icier & Baysal, 2004a). The dielectric properties of food materials such as bread, flour, fruits and vegetables depend mostly on their water content. Although, dielectric constant and dielectric loss values are generally low for fats and oils, an increase in dielectric loss with temperature can also be observed (Icier & Baysal, 2004a).

The variation of dielectric properties with temperature and microwave frequencies was investigated for solutions containing salt, sugar and carboxymethylcellulose (CMC) (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 2005). Based on the results, it was concluded that CMC does not have any significant effect on the dielectric properties whereas it has an effect on the viscosity. For sugar solutions, dielectric constant increases with the temperature and the sugar concentration. However, the dielectric loss factor decreases with sugar concentration due to the non-polar nature of sugar, however it was also found that the dielectric loss factor increases with temperature. Thus, sugar, salt and CMC can be used to mimic the dielectric properties and rheological properties of the food product to be processed (Coronel et al., 2005). For natural honey with 18% moisture content, the dielectric loss increases with temperature for frequencies above 1 GHz. The dielectric loss of honey was found to increase with water content at low frequencies due to ionic conduction (Guo, Liu, Zhu, & Wang, 2011). Boldor, Sanders, and Simunovic (2004) investigated the dielectric properties of in-shell and shelled peanuts at various densities, temperature and moisture content over a frequency range of 300 to 3000 MHz. At microwave frequencies of 915 and 2450 MHz, the dielectric properties were found to be dependent on temperature for low moisture content samples. On the other hand, at higher moisture contents, the dielectric properties were found to be less significant on temperatures (Boldor et al., 2004).

2.2. Measurement of dielectric properties

The dielectric properties can be measured by various techniques such as lumped circuit, resonator, transmission line and free space method. The lumped circuit method is suitable for frequencies below 100 MHz and not suitable for low loss materials. The cavity resonator technique can be used for frequencies between 50 MHz and 100 GHz. This technique is applicable to high or low temperatures and also for very low loss materials (loss tangent in the range of 10^{-6}). Transmission line method is generally applicable for liquid and solid materials but not for gases since their permittivity is very low. This method can be applied for frequencies ranging within 30 MHz–100 GHz. Free space method is used for measuring large, flat, thin and parallel-faced samples and is applied for high frequencies (3 GHz to 100 GHz). This method is nondestructive and noncontacting and hence can be used for measuring at very high temperatures. (Icier & Baysal, 2004b; Ryynanen, 1995).

2.3. Dielectric property measurements—applications

Nelson, Forbus, and Lawrence (1995) assessed the maturity of peaches with the help of microwave permittivity. Fresh peaches of three varieties, Dixired, Redhaven and Windblo were selected based on their different stages of maturity. The Dixired variety was the earliest to mature which is followed by Redhaven and finally by the Windblo variety. Permittivity values of peaches at 0.2 GHz and 10 GHz are related to various stages of maturity which are also dependent on the variety. Permittivity measurements were carried out using open-ended coaxial line probe and network analyzer. It was found that at 0.2 GHz an increase in dielectric constant was observed with maturity whereas the dielectric loss displayed little dependence on different stages of maturity. In contrast, at 10 GHz, dielectric loss was found to increase with maturity whereas the dielectric constant did not show any dependence upon various maturity stages. The various stages of maturity can be distinguished with the help of permittivity maturity index which is defined as the ratio of the loss tangent of a sample at two different frequencies especially at lower and higher ranges of frequency. Similarly, Nelson (2003) carried out permittivity measurements for samples cut from fruits and vegetables (apple, banana, avocado, cantaloupe, carrot, cucumber, grape, orange and potato) over a frequency range of 10 MHz to 1.8 GHz and at various temperatures ranging from 5 °C to 95 °C. The dielectric loss factor was considerably decreased with frequency whereas a slight decrease in dielectric constant was observed with frequency. Similarly, the dielectric loss factor was generally found to be increased with temperature. On the other hand, dielectric constant was found to be increased with temperature at lower frequencies whereas it decreased with temperature at higher frequencies. For fruits and vegetables with higher moisture content, the dielectric constant is generally higher over temperature ranges from 5 °C to 95 °C, due to the presence of a greater amount of water content in the tissue sample. At low frequencies in the range of 200 MHz to approximately 1–2 GHz, the loss factor is influenced by the ionic conduction mechanism. For frequencies between 1 and 2 GHz the dielectric mechanism shifts from ionic conduction to dipole polarization and for frequencies above 2 GHz dipolar relaxation mechanism dominates the dielectric loss behavior (McKeown, Trabelsi, Tollner, & Nelson, 2012). It was observed that at low frequencies, carrot showed the highest magnitude of permittivity values (dielectric constant and dielectric loss). The dielectric constant value was found to be in the decreasing order of fruits and vegetables: carrot, avocado, cantaloupe, orange, potato, banana, cucumber, grape and finally apple. Similarly, with respect to dielectric loss the decreasing order is: carrot, avocado, banana, grape, cantaloupe, potato, orange, cucumber and apple. Although moisture content did not correlate with the dielectric properties, other factors such as density, tissue structure, nature of water binding to constituents of fruits and vegetables might have affected the dielectric properties.

2.4. Microwave dielectric spectroscopy

Microwave dielectric spectroscopy is an emerging technique used to characterize and determine the quality of food products (Bohigas, Amigo, & Tejada, 2008). This technique is based on the measurement of dielectric properties which can be used to determine the sugar content in yoghurt at various frequencies (1 GHz to 20 GHz). The dielectric constant decreases with the sugar concentration (0–15%) in yoghurt (Bohigas et al., 2008). Lougovois, Kyranas, and Kyrana (2003) investigated the freshness quality and remaining storage life of iced gilthead sea bream (*Sparus aurata*) by sensory evaluation, k_1 value, GR Torrymeter (permittivity measurement) and bacterial count. At a frozen state, the maximum storage life of the fish can be extended (up to 16 days) owing to the prolonged lag phase of most bacteria. The changes in the dielectric properties of fish skin and fish muscle relate to spoilate rate and hence used as an indicator to determine quality. Since, GR Torrymeter works on the principle of dielectric measurement, Torrymeter values greater than 11 indicate fresh fish whereas a value of 6 denotes marginal quality by which the fish might have reached a storage life of 16 days. GR Torrymeter offered a fast and reliable method for sensory assessment and the accuracy of determining shelf life period is lesser than that of other quality measurement techniques (Lougovois et al., 2003). McKeown et al. (2012) investigated the moisture prediction in Vidalia onions using dielectric spectroscopy measurements. The measurement of dielectric properties was carried out using an open-ended coaxial-line probe and a network analyzer over a range of 200 MHz to 20 GHz. It was observed that at all frequencies, dielectric constant was found to increase with moisture content. Meanwhile, dielectric loss exhibited similar behavior at higher frequency ranges. It was found that model predictions incorporating density independent function of the dielectric properties may be used to predict moisture content at higher frequencies (McKeown et al., 2012). Similarly, the quality of south Atlantic hake (*Merluccius capensis*) during long term frozen storage can be determined by measuring the dielectric properties of individual fish (Kent et al., 2005). The dielectric properties were measured in the microwave region using an open ended coaxial sensor and a time domain reflectometer. It was observed that the loss of quality was more predominant when the frozen samples were stored at −10 °C, moderate loss of quality observed at −20 °C and weaker loss at −30 °C. Hence a higher storage temperature led to a higher level of deterioration (Kent et al., 2005). Microwave dielectric spectroscopy was also used to determine the low meat quality of pork in a rapid and non-destructive manner (Castro-Guraldez, Aristoy, Toldra, & Fito, 2010). Thus knowledge of dielectric properties is not only used to predict the microwave absorbing capabilities of a food material, it is also used to characterize and determine the quality of food materials.

2.5. Non-uniform temperature distribution

Even though microwave heating is volumetric and hence is more uniform compared to many traditional heating methods, non-uniform temperature distribution is one of the major problems associated with the microwave heating. Due to non-uniform temperature distribution, few regions of the material get heated very rapidly, whereas the remaining region gets heated to a lesser extent. Because of uneven temperature distribution, microorganisms are not fully eradicated during microwave pasteurization (Vadivambal & Jayas, 2010). The significant parameters which can affect the non-uniformity are penetration depth, microwave flux and the duration of microwave heating (Lobo & Datta, 1998).

Microwave pasteurization of ready-to-eat meals shows that the multimode (2450 MHz, 1.5 kW) and single mode tunnel (896 MHz, 7 kW) microwave systems were shown to display different temperature distributions. Temperature distribution was measured by inserting a thermocouple probe at the center, at the four corners and at mid-way along each edge. In a multimode tunnel domestic oven, the corners were the hottest, the edges were relatively less hot and the center region exhibited the lowest temperature. In contrast, in the single mode tunnel, the corners were cooler than the edges and overall, a more uniform temperature distribution was observed by Burfoot, Griffin, and James (1988). In multimode microwave ovens, the use of a turntable reduces the non-uniformity in the temperature of food products. Microwave heating of frozen and refrigerated food (lasagna and shepherd's pie) was investigated and it was found that in the absence of a turntable, a significant difference in temperature distribution was observed between different regions (Fakhouri & Ramaswamy, 1993). Microwave heating of liquid (water, sauce), solid (mashed potatoes) and multicomponent food (mashed potato and sauce) were investigated by James, Swain, James, and Swain (2002). The mean temperatures at hot and cold spots were found to be 83.9 and 61.7 °C, respectively for water whereas for multicomponent food, the hot and cold spots correspond to 91.8 and 36.7 °C, respectively. Thus, the temperature distribution was found to be less uniform for multicomponent food than that of water (James et al., 2002).

The size and shape of the food materials affect the temperature distribution. Three different shapes such as, brick, cylinder and hexagonal prism with three different volumes were studied to determine non-uniform temperature distribution of potato samples (Vilayannur, Puri, & Anantheswaran, 1998). For brick shaped samples, the hot spot occurred at the corner whereas the cold spot occurred at the geometric center. For cylinder shaped products, the hot spot occurred at the center whereas for hexagonal prism samples, the hot spot was found to be at the boundary regions. It was also reported that the hexagonal prism shaped products provided more uniform temperature distribution than cylinder or brick shaped products (Vilayannur et al., 1998). In another study, hot spots were found to be at the center for spherical shaped products whereas for cylindrical products, high temperature was observed at the center as well as at the surface. For cube shaped samples, most of the microwave energy was concentrated at the center (Campanone & Zaritzky, 2005). Hence, hot spots generally occur at the center than at other regions for slab shaped as well as cylindrical materials.

Pseudofood (3% agar gel) within a cylindrical glass beaker was heated in a 2.45 GHz microwave oven and was shielded by an aluminum band of low thickness (0.002 cm) at different spacings and orientations (Ho & Yam, 1992). The authors concluded that with appropriate shielding, the temperature uniformity can be ensured whereas without shielding the temperature uniformity was poor (Ho & Yam, 1992). The unevenness of microwave heating can also be caused by the standing wave effect and the rapid decay of microwave (Rattanadecho, 2004). Non-uniformity due to standing wave can be reduced by using metallic stirrers and turn tables in domestic ovens (Rattanadecho, 2004).

The solutions proposed to decrease non-uniformity in temperature distribution during microwave heating are (i) combining conventional and microwave heating, (ii) controlling the food geometry, (iii) providing shielding using metallic bands at suitable spacing and orientation, (iv) providing suitable microwave oven design, (v) manipulating the heating cycle and (vi) heating with reduced microwave power for a long duration (Vadivambal & Jayas, 2010). Also, the thickness of the food samples can be limited (up to 25 mm) and the thin samples can be stacked together to obtain limited thickness to provide uniform temperature distribution (Ohlsson & Thorsell, 1984). The above solutions suggested by various researchers are confined to specific conditions and thus cannot be generalized (Vadivambal & Jayas, 2010). Microwave energy is largely used in the industries for tempering of meat, pasta drying, tempering of frozen foods, etc. A major improvement in the temperature distribution might provide a good scope for utilizing microwave for various industrial processes (Vadivambal & Jayas, 2010).

3. Microwave cooking

Cooking is one of the major applications of microwave. In this section, various reports on the effects of microwave on cooking parameters such as quality, taste and color retention for various food materials are reviewed. There are numerous reports on the baking of bread and cooking of rice and meat using microwaves. In many cases, a comparison is also made between microwave cooking and traditional cooking. In bread baking process, it is essential to obtain browning and good texture at a fixed moisture level (Icoz, Sumnu, & Sahin, 2004). Conventional baking using hot air provides suitable color and texture. In microwave baking, sufficient brown color on the surface of breads and crust formation were not possible. During microwave heating, the air surrounding the food product is cold and water evaporating from food gets condensed on contact with cold air, which results in the lack of crispness of the food product. Susceptors were placed at the bottom of the sample to provide crust formation and surface browning of the food product. Note that, susceptors are microwave absorbing materials, which convert microwave energy to heat and supply the heat to the weak microwave absorbing materials by means of conduction and radiation. The color measurements were carried out using a chroma meter as L^*, a^* and b^*. L^* is a measure of lightness, a^* is a measure of greenness to blueness while b^* is a measure of redness to blueness. Lightness values were found to decrease with baking time and temperature which indicated that the color of the sample became darker. The results showed that zero order kinetics can explain the change in lightness using microwave. Browning was not observed without the help of susceptors (Icoz et al., 2004). Baking of bread using different heating modes such as jet impingement, microwave plus jet impingement and microwave plus infrared were also investigated by Sumnu, Datta, Sahin, Keskin, and Rakesh (2007). A crisp crust and brown color can be obtained with microwave along with jet impingement. Jet impingement baking is carried out by applying high speed convection with the help of a commercial electrical oven. The air jets were introduced from top to bottom at a velocity of 10 m/s. Microwave–impingement combination baking is achieved by combining high speed convection heat with microwaves using the same JET oven. Here, microwaves were introduced from the top and the air jets were introduced from both top and bottom at a velocity of 10 m/s. Microwave infrared baking combines both microwave and infrared heating. In the combination oven, halogen lamps were provided at the top (oven ceiling) and bottom (oven floor) and a rotary table was provided to improve heating uniformity of the samples. The results showed that the temperature was higher in a microwave–infrared combination, intermediate in a microwave–impingement combination and lower in a JET oven. Maximum moisture was retained in breads baked in JET compared to those baked in other combined modes. Since, microwave plus infrared heating did not develop a good, rigid outer crust, the temperature at the surface was lower and a lot of moisture had escaped. This results in the reduction of the final volume of the bread (Sumnu et al., 2007). Based on these reports, it is concluded that microwave heating alone or in combination with other modes of heating (hot air or infrared) for baking process does not provide better end product qualities compared to that of conventional baking.

Staling of breads refers to the changes occurring after the removal of a bread sample from the oven and it might occur at different rates and intensities (Ozkoc, Sumnu, Sahin, & Turabi, 2009). The changes include microbial deterioration, loss of flavor, loss of crispness in the crust, increased crumb firmness, amylopectin retrogradation and loss of moisture content. Ozkoc et al. (2009) investigated the staling of breads baked in different ovens. The moisture content of microwave-baked breads was found to be lowest among the samples. Due to large heat generated throughout the sample volume during microwave heating, an interior pressure gradient is found to be developed. This creates an outward flux of rapidly escaping vapor. Microwave-baked samples were found to have the highest hardness values, setback viscosities, total mass crystallinity values and retrogradation enthalpies among other heating modes. This causes staling to occur quicker in microwave baked breads compared to that in conventionally baked products. Staling of breads can also be retarded to a significant extent by the addition of certain materials such as xanthan guar blend (Ozkoc et al., 2009). In summary, microwave cooking is not an ideal choice as a bread baking process and more research is required to make it a viable option.

Lakshmi, Chakkaravarthi, Subramanian, and Singh (2007) compared the energy usage and the efficiency of cooking rice by microwaves and by other domestic appliances such as an electric rice cooker (ERC) and an LPG (liquified petroleum gas) pressure cooker. Unsoaked and pre-soaked rice was employed for normal, continuous and controlled cooking. In controlled cooking, the rice and water mixture was heated up to 100 °C and after a power interruption of 5 min the heating was resumed. The efficiencies of converting electrical energy to microwave energy and microwave to thermal energy were calculated. The theoretical efficiency was defined as the ratio of minimum energy needed for cooking to the input electrical energy. The absorption efficiency was defined as the ratio of thermal energy generated to the input electrical energy. Fig. 1 shows the comparison of the results for various cooking methods, in terms of specific energy consumption for normal cooking of unsoaked and presoaked rice. Although microwave cooking of rice provided a shorter cooking time period than other cooking methods, the electric rice cooker was found to be the most energy efficient. In electric cooking of rice, the moisture content was low at the top and bottom, and it was found to be high at the center. At the top, surface evaporation causes a decrease in the moisture content whereas at the bottom, the moisture content was low due to the presence of the heat source. In the case of microwave cooking, the moisture content was nearly uniform due to volumetric heating, except at the top where the moisture content was slightly lower due to the surface evaporation (Lakshmi et al., 2007). Thus, even though the cooking duration is short and uniformity of moisture distribution is better for microwave cooking, the energy efficiency of microwave rice cooking has to be enhanced so that it can be competitive with an electric rice cooker.

Sripinyowanich and Noomhorm (2011) investigated the drying of unfrozen and frozen cooked rice in a single-mode microwave vibro-fluidized bed dryer. To obtain instant rice with a good rehydration capability, the dried cooked rice should have a good porous structure. In addition, the whiteness needs to be retained for good appearance. During cooking, rice is gelatinized due to water absorption. The water existing in bound state exhibits low dielectric constant with respect to microwave heating. A standard cooking procedure of two step soaking and steaming was followed to obtain rice which was separated with a certain texture. During drying, hot air was passed from bottom to a bed of cooked rice which was supported on a vibrating perforated plate and simultaneously microwave energy was irradiated to the fluidizing cooked rice. Mathematical models comprising of exponential and linear variations with respect to time were proposed for the determination of the effective moisture diffusivity and activation energy. Quality parameters such as whiteness, microstructure, bulk density and rehydration capability were also analyzed. Based on the results, it was concluded that no pre-freezing treatment and drying at 160 °C were required in order to ensure

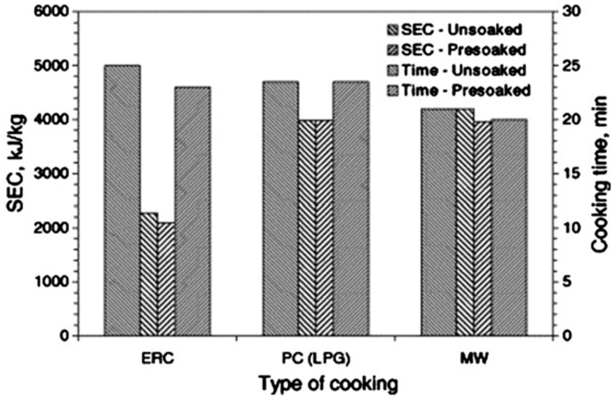

Fig. 1. Comparison of various cooking methods in terms of specific energy consumption for normal cooking of unsoaked and presoaked rice.
Reproduced from Lakshmi et al. (2007), with permission from Elsevier.

whiteness, porous structure, low bulk density and high rehydration capability (Sripinyowanich & Noomhorm, 2011).

James, Barlow, James, and Swain (2006) investigated the factors influencing the quality of pre-cooked bacon (streaky and back type) which was cooked by domestic and industrial microwave ovens at various power levels (1000 W, 800 W and 500 W). Cooking was carried out in the range of 100 °C to 145 °C, which was sufficient to pasteurize the food samples. The process parameters such as power output and cooking time had greater influence on the quality of the product than the product parameters such as bacon type and the chemical composition. Streaky bacon, which has higher fat content, showed more uniform heating compared to back bacon. In back bacon, fats were not uniformly distributed and a lesser amount of fat was located at the edges. Thus, for cooking back bacon a lower power output and longer cooking duration can yield a more uniform and acceptable product. It was also found that the presence of containers influenced the microwave field intensity and it affected the loss of weight and the processing time. Cooking was more uniform in an industrial microwave than in a domestic microwave oven, due to uniformity in magnetron position and the movement of material through the microwave system. The industrial microwave oven yielded a better and economical product by reducing the weight loss, cooking time as well as by providing uniform cooking. The most effective setting for cooking streaky bacon in a domestic microwave oven was 1000 W for 3 min with the sample kept 43 mm above the turn table. For back bacon, the most effective operation condition was 500 W for 5 min kept at the same elevation. These products have a minimum shelf life period of 11 days when stored in a vacuum at 0 °C to 4 °C (James et al., 2006).

Das and Rajkumar (2011) investigated the effects of various fat levels (5, 10, 15 and 20%) on microwave cooked goat meat patties. Each patty was cooked by microwave (700 W, 2.45 GHz) to an internal temperature of 75–80 °C. Microwave cooking time was found to decrease with an increase in fat level, as the dielectric constant and loss factor decrease with fat content. Also, a sample with high fat content might possess a lower specific heat capacity which might lead to a decrease in the heating rate. The product yield (i.e. ratio of cooked weight to the raw weight) was found to be significantly lower for 20% fat level due to high total cooking loss (15.2%). Note that, the cooking loss refers to the weight loss occurred after cooking. The cooking loss during microwave heating can be reduced by adding salt or sodium content to the meat patties. Further, it was observed that a higher fat percentage was retained by cooking 20% fat patties than that of cooking other fat patties. The shear force values of 20% fat level cooked patties were found to be the lowest due to the increase in lubrication of shear force apparatus. Visual color evaluations revealed that 5% fat level had the highest redness value whereas the highest yellowness was found in 20% fat level. Also, sensory analysis revealed that low fat levels had lesser flavor and juice than that of high fat level patties (Das & Rajkumar, 2011). Thus the amount of fat content in food materials influences the microwave heating in terms of heating rate, uniformity of temperature distribution and fat retention.

The cooking kinetics of spaghetti was studied by Cocci, Sacchetti, Vallicelli, Angioloni, and Rosa (2008) and it revealed that the total thermal effects were lower for microwave cooking as opposed to the traditional cooking (Cocci et al., 2008). Microwave cooking resulted in more gelatinized and softer products with better color retention, higher gel degree and more compact gluten network in the spaghetti outer layer. In color retention, grains with high yellow pigments were most suitable for high quality pasta making. However, traditional spaghetti cooking underwent higher color changes than that of microwave cooking (Cocci et al., 2008). In microwave cooking of chickpea, the losses in B-vitamins (riboflavin, thiamin, niacin and pyridoxine) were less than that in traditional cooking such as autoclaving and boiling (Alajaji & El-Adawy, 2006). The losses are due to the leaching and chemical destruction. Microwave cooking reduced the anti-nutritional and flatulence factors and increased the in-vitro protein digestibility and thus enhanced the nutritional value. An increase in the total essential amino acids was observed in the boiling and microwave cooking compared to that of autoclaving. Thus, microwaves improved the nutritional quality of cooked chickpea seeds and also reduced the cooking time (Alajaji & El-Adawy, 2006).

Stephen, Shakila, Jeyasekaran, and Sukumar (2010) investigated the chemical changes involved during cooking (boiling), frying, canning and microwave heating of skipjack tuna (*Katsuwonus pelamis*). The cholesterol content and the health beneficial omega-3 polyunsaturated fatty acids (ω-3 PUFA) of heat processed tuna fish were compared to that of raw fish. Fish was cooked using different procedures (i) cooked in boiling water for 100 °C, (ii) fried at 180 °C using refined sunflower oil, (iii) subjected to a standard canning procedure for canning and (iv) subjected to microwave heating for 10, 15 and 20 s. The loss in health beneficial PUFA was found to be (i) minimum with cooking or boiling, (ii) 70–85% during frying, (iii) 100% with the canning process and (iv) 20–55% with microwave heating. The cholesterol content did not increase with cooking whereas it was found to increase slightly with microwave heating and a significant increase was observed with canning. On the other hand, a decrease in cholesterol was observed during frying, probably due to the leaching of cholesterol from tuna to the frying oil. Thus, boiling and microwave heating were recommended to process tuna to retain omega-3 fatty acids (Stephen et al., 2010).

Lentil starch is an essential legume crop cultivated in Asia and Middle East countries. Gonzalez and Perez (2002) compared the effects of microwave and extrusion cooking of lentil starch based on their physical, chemical, rheological and morphological characteristics. Extrusion cooking was operated using a co-rotating intermeshing twin screw laboratory extruder at a temperature of 150 °C and at a screw speed of 90 rpm. Microwave cooking was operated at a power of 650 W for 6 min at 85 °C. The results showed that the reducing sugars increased for microwaved starch due to starch fragmentation whereas it remained constant for extruded starch. At all temperatures, the functional properties of lentil starches such as water absorption, solubility and swelling power were found to decrease for both the treatments and the decrease was more prominent in microwave cooking. The decrease in the functional properties might be due to intergranular molecular rearrangement which may lead to the lesser accessibility of the amorphous areas. The amylographic viscosities were also found to be lowered for both extruded and microwave cooked samples due to a decrease in the swelling power and solubility (Gonzalez & Perez, 2002).

Barba, Calabretti, d'Amore, Piccinelli, and Rastrelli (2008) investigated the change in phenolic constituents during microwave baking of cv. Agria potatoes (*Solanum tuberosus* L., *Agria* cultivar) at various microwave power levels. During the baking of potatoes, the need for retaining water contents in the potato matrices is necessary in order to avoid thermal damages, to preserve antioxidants, to promote the starch gelatinization process and also to provide lossy features. The baking time was found to increase with a decrease in the power level and at the same time a decrease in water losses was observed due to a slow heating rate. By reducing water loss, the thermal damages of nutritional components are avoided due to its high thermal capacity. It was found that the phenolic compound was retained at a good level when the potato samples were cooked at 500 W (Barba et al., 2008).

The dielectric components of egg components, albumen (egg white) and yolk were investigated by Dev, Raghavan, and Gariepy (2008). The dielectric properties were measured at various temperature (0–62 °C) and frequency (200 MHz to 10 GHz). It was observed that the albumen had higher dielectric properties than yolk which indicate that albumen possessed a higher heating rate than yolk. Surprisingly, it was found that the egg-shell and shell membrane were transparent to microwave due to low moisture content and the lesser extent of composition and structure of shell proteins. Consequently, for in-shell eggs, the heating rate of albumen was similar to that of yolk (Dev et al., 2008). Kumar and Sanavullah (2011) identified the locations within a microwave oven cavity to cook an egg without explosion using theoretical analysis. Eggs or packaged products are advised not to be kept in a microwave oven due to the generation of high internal pressure in the sealed objects. In an egg, the dielectric properties of albumen are higher than the yolk. Using a mathematical model, the high energy points and the low energy points were identified in the microwave oven. At high energy points, albumin got cooked fast and started to splatter whereas at low energy points the albumin was slowly cooked without explosion. A domestic microwave oven operating at a frequency of 2.45 GHz with adjustable power from 0 to 750 W and a rectangular wave guide of TE10 mode positioned at the right side of the microwave cavity was used for heating egg samples. For a microwave cavity of 29 cm × 29 cm × 19 cm, the low energy points are identified as $5 < x < 10$, $6 < y < 9$ and $2.5 < x < 5$, $5 < y < 10$ respectively. Here, the origin is at the front left corner and the y values are measured from front to back. It was recommended to keep the eggs at a low energy point and at low power (40%) in order to avoid explosion in the microwave oven (Kumar & Sanavullah, 2011).

3.1. Microwave blanching

Blanching is generally used for color retention and enzyme inactivation, which is carried out by immersing food materials in hot water, steam or boiling solutions containing acids or salts. Microwave blanching of herbs such as marjoram and rosemary was carried out by soaking the herbs in a minimum quantity of water and exposed to microwaves (Singh, Raghavan, & Abraham, 1996). Microwave blanching was observed for maximum retention of color, ascorbic acid and chlorophyll contents than that of water and steam blanching. Microwave blanched samples were found to have better retention of quality parameter than that of microwave dried samples without blanching (Singh et al., 1996). Similarly, waster-assisted microwave treatment of fresh jalapeno peppers and coriander foliage were found to have an effect against the pathogenic bacterium *Salmonella* typhimurium which resulted in the reduction of 4–5 log cycles of microbial population (De La Vega-Miranda, Santiesteban-Lopez, Lopez-Malo, & Sosa-Morales, 2012).

Blanching is also used to remove seed coat or testa which may reduce enzyme activity and moisture content and might interfere with further processing into specific products. Blanching also helps to remove damaged or discolored seeds, foreign material and dust. Schirack, Drake, Sanders, and Sandeep (2006a, 2006b); Schirack, Sanders, and Sandeep (2007) studied the microwave blanching of peanuts and found that microwave blanching was better than traditional blanching techniques in terms of energy and time savings. It was observed that the microwave blanching of peanuts at high process temperatures resulted in the occurrence of stale/floral and ashy-off flavors. The resulting off-flavors may be related to the increased concentrations of phenylacetaldehyde, guaiacol and 2,6-dimethylpyrazine which might have occurred due to the Maillard reactions and thermal degradation of microwave blanched peanuts at high temperatures (Schirack et al., 2006a). Further, impact of different microwave blanching parameters on sensory attributes of roasted peanuts was investigated by Schirack et al. (2006b, 2007). The factors examined were microwave exposure time, amount of air circulation and initial moisture content of peanuts. It was found that the highest total off note (off flavor) occurred for the treatment of 11 min without air circulation and for temperatures reaching 128 °C or higher. On the other hand, a short-duration treatment with internal temperatures not exceeding 110 °C was observed to be acceptable for microwave blanching (Schirack et al., 2006b). Similarly, peanuts with internal temperatures greater than 110 °C and a final moisture content of 5.5% or below yielded acceptable blanchability of greater than 85% of the industry standard (Schirack et al., 2007).

4. Microwave drying

In drying of food materials, the goal is to remove moisture from food materials without affecting their physical and chemical composition. It is also important to preserve the food products and enhance their storage stability which can be achieved by drying. Dehydration of food can be done by various drying methods such as solar (open air) drying, smoking, convection drying, drum drying, spray drying, fluidized-bed drying, freeze drying, explosive puffing and osmotic drying (Cohen & Yang, 1995). Solar drying and smoking are low cost techniques which were used for drying of meat and sea food products. For a continuous mode of operation, convection and drum drying can be used. Similarly, spray drying can be used for drying of liquids, instant tea and coffee in which the final product can be obtained in spherical form. In the same manner, commercialized fluidized bed dryers are used for drying of whole peas and dairy products (Cohen & Yang, 1995). Microwave drying has the advantages of achieving fast drying rates and improving the quality of some food products. The energy absorption level is controlled by the wet products which can be used for selective heating of interior parts of the sample containing moisture and without affecting the exterior parts. Microwave drying is considered very useful during a falling rate period. During the falling rate period the diffusion is rate-limiting, resulting in the shrinkage of the structure and reduced surface moisture content. However, in microwave drying, due to volumetric heating the vapors are generated inside and an internal pressure gradient is developed which forces the water outside. Thus shrinkage of food materials is prevented in microwave drying. Microwave energy combined with other drying methods can improve the drying efficiency as well as the quality of food products which is far better than that achievable by microwave drying only or by other conventional methods only (Zhang et al., 2006).

In microwave drying of parsley, performed by Soysal (2004), drying took place mainly in the constant rate period and the falling rate period. The drying time was found to decrease with an increase in the microwave output power. Microwave dried parsley leaves retained the color and the change in microwave power level did not affect the color parameters (Soysal, 2004). In another study, microwave drying of carrot slices were found to occur in the falling rate period and not during constant rate period. At high microwave power, rapid mass transfer from the center to the surface occurs due to generation of more heat. It was also found that as the slice thickness increases, β-carotene content and rehydration ratio decrease. High volumetric heating causes high internal pressure inside the samples which result in boiling and bubbling of a sample. Thus, β-carotene content and the rehydration ratio were found to be reduced (Wang & Xi, 2005).

Ozkan, Akbudak, and Akbudak (2007) examined the microwave drying of spinach leaves in order to reduce moisture content up to 99%. Above 350 W microwave power, the energy consumption remained constant. Microwave drying was found to be more efficient at operating conditions of 750 W and 350 s. At these operating conditions, optimum drying characteristics of spinach (in terms of drying time, energy consumption, color criteria and ascorbic acid level) were obtained (Ozkan et al., 2007). Lombrana, Rodriguez, and Ruiz (2010) studied the drying of sliced mushroom using a single mode microwave at 2.45 GHz. The experiments were carried out by monitoring and controlling the temperature and pressure. The samples were cut into parallelepiped pieces and the dried mushrooms were characterized with SEM and BET analysis. When the optical probe was placed in the samples at the middle of the chamber, moderate shrinkage without large voids was observed. But, if the probe was placed in samples at either edge, large voids were formed due to more vapor exiting the samples. In addition, shrinkage led to the formation of nonhomogenous structure. During microwave heating, the water present in the center of the sample gets heated more readily than the samples at the edges, resulting in the inverse temperature profile. The results showed that at low pressure and moderate microwave heating (120 W), the drying rate is high and the quality of the mushroom is also good. At low microwave power (60 W), a good quality of the mushroom was obtained at the cost of a slow drying rate whereas at high microwave power (240 W) or at atmospheric pressure condition, ineffective drying was observed along with the formation of large voids and the entrapment of moisture inside the sample. Thus drying with moderate microwave power at low pressure conditions is recommended for drying mushroom slices (Lombrana et al., 2010).

One of the disadvantages of microwave drying is that excessive temperature along the corner or edges of food products results in scorching and production of off-flavors especially during final stages of drying. This is due to the difficulty in the control of final product temperature in microwave drying whereas in hot air drying, the product temperature never exceeds the hot air temperature. The penetration depth of microwaves at 2.45 GHz is limited for large scale drying whereas radio frequency (RF) heating at 10–300 MHz can give better penetration depth. In some cases, rapid mass transport might cause change in the food texture called ‘puffing’ which might be desirable or undesirable depending on the final product (Zhang et al., 2006). Hence it is necessary to combine microwave drying with conventional drying in order to enhance drying rate as well as maintain product quality.

4.1. Microwave assisted air drying

Microwave assisted air drying is one of the methods where hot air drying is combined with microwave heating in order to enhance the drying rate. Microwave heating can be combined with hot air in three different stages of the drying process. At the initial stage, microwave heating is applied at the beginning of the dehydration process, in which the interior gets heated rapidly. At a rapid drying period, a stable temperature profile is established in such a way that the vapor is forced outside due to an improved drying rate. This creates a porous structure called ‘puffing’ which can further facilitate the mass transfer of water vapor. At the reduced drying rate period or at the final stage of drying, the drying rate begins to fall where the moisture is present at the centre and with the help of microwave heating, vapor is forced outside in order to remove bound water (Zhang et al., 2006).

For drying of high moisture fruits and vegetables, a reduction in moisture content is time consuming especially in the final stage of drying. Microwave assisted drying as the final stage of air drying overcomes these disadvantages with high thermal efficiency. Hot air drying does not improve moisture loss at the final stages of the drying process, since the diffusion process is very slow. Drying of banana is difficult as it falls under the falling rate period. But, hot air drying combined with microwave finish drying reduced the drying time by 64% as compared to convective air drying (Maskan, 2000). In drying of kiwifruits, shrinkage was found to be more predominant during sole microwave heating than that of hot air drying. But, lesser shrinkage of kiwi fruits was found to be observed with combined hot air–microwave drying. Also, kiwifruits dried by combined hot air–microwave displayed higher rehydration capacity than those of kiwifruits dried by sole microwave or hot air drying (Maskan, 2001).

During microwave assisted air-drying of apple and mushroom, a minimum air velocity of 1 m/s was required in order to prevent browning of the food samples. When compared to hot air drying, microwave assisted air drying reduced the drying time by a factor of two for apples and by a factor of four for mushrooms. Besides, the rehydration capacity of apple and mushroom dried in single mode cavity was found to be 20–25% better than food samples dried in multimode cavity (Funebo & Ohlsson, 1998). In drying of garlic cloves, microwave assisted air drying achieved a drying rate 80–90% better than that of conventional air drying, and the product of microwave assisted drying exhibited superior qualities (Sharma & Prasad, 2001). Microwave dried garlic cloves were found to be lighter in color due to the lesser browning effect and the volatile components responsible for flavor content were also retained (Sharma & Prasad, 2001).

The dehydration characteristics of thin layer carrot cubes during microwave-assisted air convective drying were investigated by Prabanjan, Ramaswamy, and Raghavan (1995). The domestic oven (600 W) was modified to allow air at a constant flow rate of 1.7 m/s and at given temperatures of 45 and 60 °C. It was observed that the microwave heating reduced drying time by 25–90% than that of conventional air drying. Also, the color of rehydrated carrots dried at lower power levels (<20%) was better than a sample dried at a higher power level of 40% (Prabanjan et al., 1995). Venkatachalapathy and Raghavan (1999) carried out microwave drying of osmotically dehydrated strawberries at different power levels. Strawberries were pretreated with 2% ethyl oleate and 0.5% NaOH in order to make the skin transparent to moisture diffusion and promote rapid dehydration by osmosis. It was observed that the quality parameters of microwave dried strawberries were equal to or better than freeze dried berries in rehydration. Due to greater internal heating, the berries are softened during microwave treatment compared to that of freeze dried berries (Venkatachalapathy & Raghavan, 1999). Also, it was observed that the shrinkage ratio (volume at any moisture content to the initial volume) of microwave dried berries increases linearly with moisture ratio (Raghavan & Venkatachalapathy, 1999).

Microwave-convective and microwave-vacuum drying of cranberries were studied by Sunjka, Rennie, Beaudry, and Raghavan (2004). The drying performance in terms of mass of water evaporated per unit of supplied energy proved that the microwave-vacuum drying was more energy efficient than microwave convective drying. On the other hand, sensory analysis (color, texture, taste, overall appearance) showed that microwave-convective dried cranberries were slightly better than that of microwave-vacuum dried cranberries (Sunjka et al., 2004). The optimal energy consumption for combined microwave assisted hot air drying of pumpkin slices was found to be 0.29 kWh which was operated at a power of 350 W and at a temperature of 75 °C. On the other hand, the energy consumption of hot air drying at 75 °C was found to be 0.61 kWh (Alibas, 2007). Gowen, Abu-Ghannam, Frias, and Oliveira (2008) developed models to predict dehydration and rehydration kinetics during combined microwave–hot air drying of pre-cooked soybeans. The dehydration and rehydration rate was found to increase with an increasing microwave power level and the air temperature. The optimal condition for combined microwave–hot air drying was found to be at a microwave power of 210 W and air temperature of 160 °C (Gowen et al., 2008).

Sousa and Marsaioli (2004a, 2004b) investigated microwave assisted drying of bananas by varying air temperature (25 to 55 °C) and air flow rate (0.8 to 1.8 m^3/min). The dried products possessed high sensory qualities, when the samples were microwave dried at air temperatures higher than 30 °C and with the air flow rate in the range of 1.1 to 1.65 m^3/min. Also, the color, sweetness and texture of the dried products were close to that of the ideal acceptance range (Sousa & Marsaioli, 2004a, 2004b). Similarly, Pereira, Marsaioli, and Ahrne (2007) observed that increasing the microwave power during final stages of microwave–hot air drying of osmotically dehydrated bananas increases the drying rate, thus reducing the drying time. At the same time, charring might also occur which can be prevented by cooling the product surface by means of providing lower air temperature or high air velocity (Pereira et al., 2007).

The drying process of macadamia nuts is critical, since the drying of the kernel requires certain controlled conditions in order to achieve minimum quality standards. Silva, Marsaioli, Maximo, Silva, and Goncalves (2006) investigated the feasibility of drying macadamia nuts by applying a microwave assisted hot air drying process. It was found that the microwave assisted drying achieved in reducing the drying time (4.5–5.5 h) and increasing the quality of the kernels as compared to that of conventional processes (~144 h). It was observed that the quality of the product did not deteriorate with respect to oxidative reactions occurring during the six month storage period. Further, the sensory quality tests proved that the microwave assisted dried products did not differ significantly from the conventionally dried products (Silva et al., 2006).

The efficiency of microwave assisted air drying of *Penne* short cut pasta using microwave assisted hot air rotary dryer was investigated by Berteli and Marsaioli (2005). It was observed that the average drying time of microwave assisted drying (18–19 min) was reduced by a factor of 10 times compared to that of conventional air drying (6.5 h) and with respect to space utilization microwave drying occupied 10% of the floor space than that of conventional hot air dryer (Berteli & Marsaioli, 2005). Table 1 shows the experimental conditions applied for the microwave assisted drying of various food materials.

In summary microwave assisted air drying is found to be helpful at the final stages of drying food products especially for fruits and vegetables. Besides increasing the drying rate, microwave assisted air drying enhances the rehydration capacity of dried products and also overcomes shrinkage problems.

4.2. Microwave assisted vacuum drying

During vacuum drying, high energy water molecules diffuse to the surface and evaporate due to low pressure. Because of this, water vapor concentrates at the surface and the low pressure causes the boiling point of water to be reduced. Thus vacuum drying prevents oxidation due to the absence of air, and thereby maintains the color, texture and flavor of the dried products. In the absence of convection, either conduction or radiation or microwaves can be combined with vacuum drying to improve its thermal efficiency (Zhang et al., 2006).

Vacuum microwave drying of banana slices was examined at a microwave power supply of 150 W and under a vacuum of less than 2500 Pa (Drouzas & Schubert, 1996). It was determined that the drying was achieved in less than 30 min without exceeding 70 °C and the quality of the product was found to be good and was comparable to that of a freeze-dried product. The dried product also provided excellent taste and flavor with no shrinkage or change in color (Drouzas & Schubert, 1996). In microwave vacuum drying of model fruit gel (simulated concentrated orange juice), a reduction in the moisture content from 38.4% to less than 3% was achieved in less than 4 min whereas conventional air drying took more than 8 h to reach 10% moisture (Drouzas, Tsami, & Saravacos, 1999).

A study on microwave vacuum drying of carrot slices showed that the microwave vacuum dried products had higher α-carotene content and vitamin C content, softer texture, had higher rehydration potential and lesser color deterioration than that of air drying (Lin, Durance, & Scaman, 1998). The losses of α and β-carotene content was found to be very low due to rapid heating rate and depletion of oxygen during vacuum operation. Vitamins are generally sensitive to the thermal damage and oxidation, whereas microwave vacuum drying eliminates both and hence high quantities of vitamins were retained (Lin et al., 1998). In another study, microwave vacuum drying of carrot slices which were subjected to microwave at 400 W power retained 88% of the β-carotene (Mayer-Miebach, Behsnilian, Regier, & Schuchmann, 2005). The processing time of the microwave vacuum drying at 70 °C was found to be shorter (1.5 h) compared to that of convective drying (3.5 h). But, microwave vacuum drying at high power (600 W) led to a significant loss of β-carotenes. In summary, microwave drying at moderate power causes a low loss of β-carotenes while reducing operation time (Mayer-Miebach et al., 2005).

Hu, Zhang, Mujumdar, Xiao, and Sun (2006, 2007) investigated the hot air and vacuum microwave drying of edamames and found that sequentially combining hot air and vacuum microwave drying provided better drying results compared to that of vacuum microwave drying or air drying. Fig. 2a and b show the effect of microwave power and vacuum pressure on the drying time (Hu et al., 2006). The drying time is significantly reduced with an increase in the microwave power intensity as well as a decrease in the mass load. Applying high vacuum tends to improve the evaporation and volatilization of water from the material, whereas it may lead to electrical arcing which might result in the overheating of the product. The optimal drying conditions of edamames was given as: i) hot air drying at 70 °C for 20 min and ii) vacuum microwave drying at a power intensity of 9.33 W/g and at a vacuum pressure of 95 kPa (gauge pressure) for 15 min (Hu et al., 2006, 2007). In another study, the kinetics and the drying characteristics of vacuum microwave dried potato slices were investigated at various microwave power levels (140, 240 and 340 W) and vacuum pressure (40, 60 and 80 kPa) (Song, Zhang, Mujumdar, & Fan, 2009). Although, a higher heating rate was achieved by employing high microwave power and low pressure, the effect of low pressure was not as significant as that of increasing microwave power (Song et al., 2009). Table 2 shows the microwave assisted vacuum drying of various food materials.

In summary microwave vacuum drying is applied for heat sensitive materials such as banana, carrot, potato, etc. The loss of nutritional qualities (vitamins, α and β-carotenes etc.) of food products by microwave vacuum drying is minimum due to nonexposure of heat and oxygen.

4.3. Microwave assisted freeze drying

Freeze drying is considered as a gentle dehydration technique applied for heat sensitive foods, and pharmaceutical and biological materials (Zhang et al., 2006). In freeze drying, the temperature is lowered and, by applying vacuum or low pressure, the frozen water is directly

Table 1
Microwave assisted air drying of various food materials.

S. No.	Product dried	Optimum experimental conditions			References
		Air velocity	Air temperature	Microwave power	
1.	Pumpkin slices	1 m/s	75 °C	350 W	Alibas (2007)
2.	Apple	1 m/s	60 °C	0.5 W/g	Funebo and Ohlsson (1998)
3.	Mushroom	1.5 m/s	80 °C	0.5 W/g	Funebo and Ohlsson (1998)
4.	Banana slice	1.45 m/s	60 °C	350 W	Maskan (2000)
5.	Kiwifruits	1.29 m/s	60 °C	210 W	Maskan (2001)
6.	Carrots	1.7 m/s	45 and 60 °C	120 and 240 W	Prabanjan et al. (1995)
7.	American ginseng roots	60 l/min	40 °C	60 W	Ren and Chen (1998)
8.	Tilapia fish fillets	2 m/s	50 °C	400–600 W	Duan, Jiang, Wang, Yu and Wang (2011)

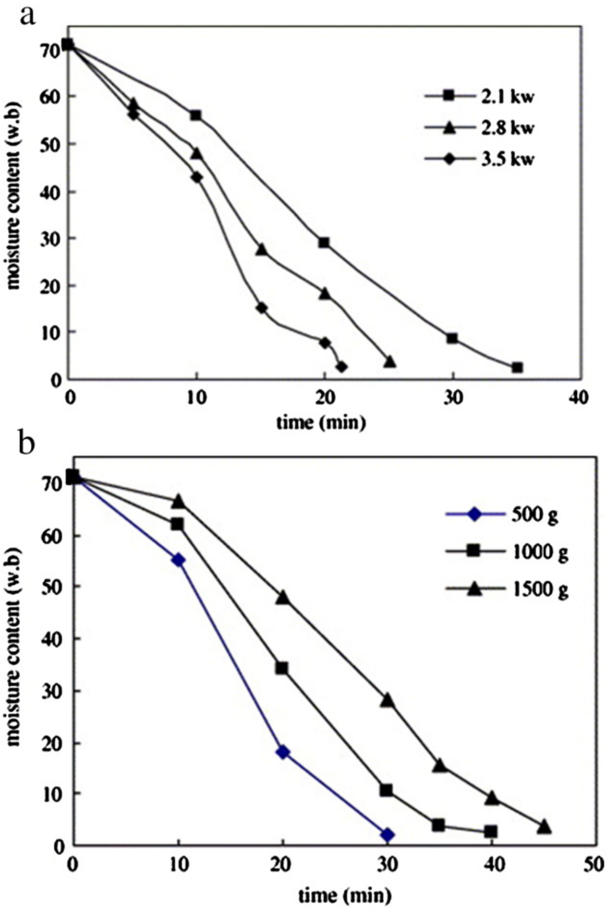

Fig. 2. a: Effect of microwave power on drying time. b: Effect of vacuum pressure on drying time.
Panel a was reproduced from Hu et al. (2006), with permission from Elsevier. Panel b was reproduced from Hu et al. (2006), with permission from Elsevier.

transferred to the vapor phase without going through the liquid phase. Thus the pores are preserved and those can be rehydrated quickly. The loss in terms of flavor can also be minimized using this method. Since freeze drying is time consuming, this method is applied only for high premium or heat sensitive materials (Cohen & Yang, 1995). Microwave freeze drying can be applied in two different ways, such as i) freeze drying accompanied concurrently with the help of microwave and ii) microwave drying applied after freeze drying (Duan, Zhang, Mujumdar, & Wang, 2010a). In the first type, the whole drying process takes place under vacuum environment and a microwave field is applied to supply the heat of sublimation required for freeze drying. In the second type, the drying process was divided into two stages, (i) freeze drying followed by (ii) microwave/vacuum microwave drying (Duan et al., 2010a). Freeze drying combined with microwaves offers advantages like reduced processing time and better product quality (Zhang et al., 2006). The quality of freeze dried products is better than other conventional drying methods due to its low processing temperature and lack of oxygen in the process. However, freeze drying is an expensive and lengthy dehydration process, which leads to small throughput and high capital and energy costs (Duan et al., 2010a; Zhang et al., 2006). Since microwave energy does not interact well with ice, thermal runaway might occur due to the localized melting in the frozen zone and this can be a problem during microwave assisted freeze drying. Also, in industrial applications plasma discharge/arcing might occur which result in the poor product quality and may also eventually lead to the destruction of the food products. The chance of plasma occurring is related to the pressure in the chamber. To minimize the probability of arcing, it was suggested to operate at low microwave power during low pressure operations. Also, cycling the pressure from low to moderate might also control the plasma discharge. Thus the chamber pressure becomes a suitable control parameter to control and avoid plasma discharge. In general, microwave freeze drying is a complex control problem (Zhang et al., 2006).

Duan, Zhang, Li, and Mujumdar (2008) and Duan, Zhang, Mujumdar, and Wang (2010b) evaluated microwave freeze drying of sea cucumber combined with nanoscale silver. Nanoscale silver has a wide range of antibacterial property since it can easily penetrate into cell organisms and inactivate certain enzymes. Fig. 3 shows the schematic diagram of the setup for microwave freeze drying of food materials (Duan et al., 2010b). Microwave freeze drying combined with the nanoscale silver coating significantly reduced the microorganism count than microwave freeze drying of sea cucumber without the coating. Coating with nanoscale silver did not affect the drying efficiency and sensory qualities of microwave freeze drying (Duan et al., 2008). During microwave freeze drying of sea cucumber, efforts were made to reduce the corona discharge or arcing which might eventually cause burning or overheating of food materials. It was reported that the pressure in the range of 100–200 Pa may readily cause corona discharge and hence pressure in the range of 50–100 Pa was suggested for microwave freeze drying. It was also recommended to reduce microwave power at low moisture conditions since air discharge might take place due to a decreasing moisture content (Duan et al., 2010b). In microwave freeze drying of cabbage, the drying rate of microwave freeze drying was twice greater than that of vacuum freeze drying. Microwave freeze drying affected the drying rate of falling rate drying period more significantly than that of constant rate drying period. The drying rate of microwave freeze drying was found to increase with a decrease in the material thickness and

Table 2
Microwave assisted vacuum drying of various food materials.

S. No.	Product dried	Vacuum range	Microwave power	Significant results	References
1.	Edamames	−95 kPa	700 to 4200 W	Deep-bed drying of greater depth creates larger moisture gradients	Hu et al. (2007)
2.	Carrot slices	100 mm Hg	4 kW	VMD provided better sensory attributes than freeze drying	Lin et al. (1998)
3.	Potato slices	−0.04 to −0.06 MPa	1.4–3.4 W/g	Effect of vacuum pressure on drying rate not as significant as microwave power	Song et al. (2009)
4.	Wild cabbage	2–2.5 kPa	1400–3800 W	The retention of chlorophyll and ascorbic acid was significantly improved	Yanyang, Min, Mujumdar, Le-qun and Jin-cai (2004)
5.	Starch	5 kPa	600–1500 W	Simultaneous moisture removal and significant improvement in water absorption capacity	Mollekopf, Treppe, Dixit, Bauch and Fuhrlich (2011)
6.	Mixed apple with potato chips	5 kPa	4 W/g	Microwave vacuum drying achieved lower energy consumption and shorter drying than microwave freeze drying	Huang, Zhang, Mujumdar and Lim (2011)
7.	Tomatoes	6.65 kPa	4–20 kW	Drying was much faster towards the end of the process	Durance and Wang (2002)
8.	Mushrooms	6.5–23.5 kPa	115–285 W	70–90% decrease in drying time than hot air drying	Giri and Prasad (2007)
9.	Cranberries	3.4–6.6 kPa	1–1.25 W/g	Better than microwave air drying in terms of energy consumption and drying time	Sunjka et al. (2004)
10.	Mint leaves	13.33 kPa	8–11.2 W/g	Color retention was higher than microwave air drying	Therdthai and Zhou (2009)

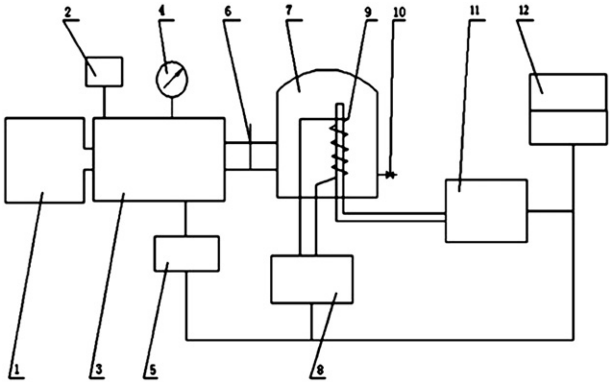

Fig. 3. Schematic diagram of microwave freeze drying setup.
Reproduced from Duan et al. (2010b), with permission from Elsevier.

the cavity pressure. Further, microwave freeze drying had significant sterilization effects on the food material due to the combined thermal and biological effects leading to the death of microorganisms (Duan, Zhang, & Mujumdar, 2007).

High maturity banana slices containing high sugar content, and hence high drying rates, were observed for microwave assisted freeze drying (Jiang, Zhang, & Mujumdar, 2010a). It may be noted that sugar molecules have a higher loss factor than ice crystals and hence they absorb more microwave energy and convert it to heat efficiently. High maturity samples displayed better quality parameters such as color, rehydration ratio and hardness than those of low and medium matured samples. At the same time, high maturity samples lead to uneven heating due to more sugar content. This results in the poor appearance of the product caused by the expansion of sugar molecules due to uneven heating. On the other hand, sensory qualities were found to be better retained by the medium matured samples (Jiang et al., 2010a). In microwave freeze drying of banana chips, serious damage was found to occur at the primary drying stage due to thawing and hence greater change in the expansion ratio was found to occur in the secondary drying stage (Jiang, Zhang, & Mujumdar, 2010b). This causes drastic changes in the starch and sugar content, as well as color and structure. Hence it was recommended to operate at gentle conditions during the primary stage of freeze drying in order to obtain a high quality of products (Jiang et al., 2010b).

Wang, Zhang, Mujumdar, and Sun (2009) and Wang, Zhang and Mujumdar (2010) investigated the microwave freeze drying of instant vegetable soup and it was reported that the microwave power influenced the drying rate as well as sensory qualities of the dried product. The vegetable soup mix contained ingredients such as cabbage, carrot, tomato, spinach, mushroom, water, salt, sugar and monosodium glutamate in certain proportions. After cooling, the soup was kept in a refrigerator until it reaches a temperature of −30 °C. The optimal drying of vegetable soup with a thickness of 15–20 mm and 450 g can be attained at a temperature of 50–60 °C and at a microwave power of 450–675 W. Although drying time was found to be reduced with the decreasing material load and thickness, too thin a material might cause the deterioration of the material (Wang et al., 2009). In another study, NaCl and sucrose content had a significant effect on the drying rate of instant vegetable soup, while sodium glutamate had no significant effect on the drying rate (Wang et al., 2010). The optimal vegetable soup ingredients required for obtaining better drying characteristics during microwave freeze drying was found to be 3.2–5.3 g of NaCl per 100 g of water, 2–6.8 g of sucrose per 100 g of water and sodium glutamate content of less than 4.5 g per 100 g of water (Wang et al., 2010).

Most of the microwave assisted drying of fruits and vegetables were performed in lab scale and hence more industrial scale applications with optimizations need to be conducted (Zhang et al., 2006). Also, the optimal combination of microwave drying combined with other drying methods need to be determined in order to find suitable microwave power, type of drying and order of combination of microwave and conventional treatment (Zhang et al., 2006). The energy consumption for microwave vacuum drying is very low compared to that of other microwave assisted processes and hence it can be used for large scale production. Microwave freeze drying has the advantages of obtaining products of high quality and better appearance. However, more studies on process modeling and optimization need to be conducted to accurately predict the drying rate, energy efficiency and product quality (Zhang et al., 2006). The manufacturing of a larger microwave system with a good control unit suitable for food production also needs to be studied in order to utilize the pilot scale results in industrial level applications. Also, special phenomena such as hotspots, thermal runaway and plasma discharge/arcing need to be studied in detail, to eliminate them during microwave-related combination drying (Zhang et al., 2006).

5. Microwave pasteurization and sterilization

Pasteurization and sterilization are done with the purpose of destroying or inactivating microorganisms to enhance the food safety and storage life (Nott & Hall, 1999). In order to ensure that pathogenic microorganisms are killed, the food material is maintained at a particular temperature for a particular period of time. Pasteurization is a process in which pathogenic microorganisms such as bacteria in the vegetative form are destroyed by the thermal treatment. Pasteurization also involves inactivation of undesirable enzymes which causes cloud loss in certain juices.

Pasteurization can be achieved by novel thermal (RF and ohmic heating) and non-thermal technologies (high hydrostatic pressure, UV treatment, pulsed electric field, high intensity ultrasound, ionizing radiation and oscillating magnetic field) without affecting the color, flavor or nutritive value of food materials (Pereira & Vincente, 2010). In ohmic heating, the heating occurs due to the electrical resistance caused by the food materials when a current is passed through them. For a pulsed electric field process, a very high voltage was applied for a very short time through the fluid. This generates mild heat and cell disruption of microorganisms occurs due to electroporation. During a high hydrostatic pressure process, pressures of 100 to 1000 MPa were applied and as a result, large microorganisms or enzymes consisting of large molecules were affected. This technique is used for the aroma components for which the sensory and nutritional qualities need to be maintained. The advantages of a high hydrostatic pressure process are the release of minimal heat, homogeneous nature of the process and its applicability to packaged materials. Most of the novel and non-thermal techniques provide energy savings up to 70% compared to the traditional cooking methods (Pereira & Vincente, 2010).

5.1. Microwave pasteurization—mechanism

Destruction of microbes or enzymes by microwave or radio frequency waves at sublethal temperatures was explained by one or more of the following theories: selective heating, electroporation, cell membrane rupture and magnetic field coupling (Kozempel, Annous, Cook, Scullen, & Whiting, 1998). The selective heating theory suggests that the microorganisms are selectively heated due to microwaves and reach a temperature higher than that of the surrounding fluid. This causes the microorganisms to be destroyed more quickly. According to the electroporation theory, the electrical potential across the cell membrane causes pores, which results in the leakage of cellular materials. In the cell membrane rupture theory, cell membrane is ruptured due to the voltage applied across the cell membrane. According to the magnetic field coupling theory, the internal components of the cell are disrupted due to the coupling of electromagnetic energy with critical molecules such as protein or DNA (Kozempel et al., 1998). Although various theories suggest the non-thermal effect of microwaves, it was further observed that in the absence of other stresses such as pH or heat, microwave energy did not inactivate microorganisms. However, a significant enhancement or magnification of thermal effects might have been caused by microwaves (Kozempel, Cook, Scullen & Annous, 2000). Regardless of the exact origin of the enhancement of thermal effect, it is clear that microwaves are effective in the destruction of microorganisms or inactivation of enzymes.

5.2. Microwave pasteurization of fluid food materials

The application of microwave pasteurization has been largely applied to fluid foods such as pasteurization of fresh juices and sterilization of milk. Microwave pasteurization of fresh juice and microwave sterilization milk were reviewed by Salazar-Gonzalez et al. (2012). Microbial and enzyme inactivation of various fluid foods such as apple juice, apple cider, coconut water, grapewater juice, milk and sweet potato puree were reviewed. It was reported that with the knowledge of dielectric properties, the appropriate conditions for applying microwave energy and desired process lethality could be obtained (Salazar-Gonzalez et al., 2012).

5.3. Microwave pasteurization of solid food materials

Pasteurization of in-shell egg can be achieved with the help of microwaves (Dev et al., 2008). It was known that the albumen had higher dielectric properties than the yolk. On contrary, microwave heating of in-shell egg did not show any significant difference in the heating rate of albumen and yolk. The enhanced interior heating might be due to the combination of egg geometry, dielectric properties and size of the egg. It was shown that the microwave pasteurization of shell eggs can be achieved without losing the shell integrity of eggs (Dev et al., 2008). In another study, microwave pasteurization was used for the inactivation of *Salmonella* typhimurium in the yolk of shell eggs (Shenga, Singh, & Yadav, 2010). A 22% reduction of microbes was attained for microwave irradiation of 15 s whereas 36% reduction was achieved by moist heat treatment of 15 min (Shenga et al., 2010).

Microwave pasteurization of pickled asparagus achieved the required temperature for pasteurization twice as fast as (15 min for 1 kW and 9 min for 2 kW) conventional heating (30 min). The thermal degradation of asparagus was more when it was subjected to conventional treatment compared to when it was subjected to microwave heating (Lau & Tang, 2002). Similarly, microwave pasteurization was able to achieve 2-fold reduction in the number of *Alicyclobacillus acidoterrestris* spores in a cream of asparagus at the following process conditions: 100% microwave power for 5 min, 90% microwave power for 6 min and 80% microwave power for 7 min (Giuliani, Bevilacqua, Corbo, & Severini, 2010).

5.4. Microwave sterilization

Packed food products can be sterilized using various novel techniques such as UV light, microwave irradiation, ozone and cold plasma (Guillard, Mauricio-Iglesias, & Gontard, 2010). There are cases for which food materials can be treated as such while others in the packed conditions. Packaging materials consists of low molecular weight compounds (plasticizer, reticulants, anti-oxidants, etc.) which might degrade and migrate into food materials. Several substances such as plasticizers and benzene were found to have non-negligible toxicological effect that had migrated in quantities higher than the permitted values. Ozone, due to its strong oxidant nature either in gaseous or aqueous form, could be used as a disinfectant for treating foods and food packaging materials. Similarly, UV light in the wavelength range of 250–280 nm is found to be effective against micro-organisms. However, it was found that ozone and UV light might cause cross linking or degradation of polymers in food packages. This results in the formation of new byproducts and can migrate into the food materials. Similarly, during high temperature microwave heating, benzene was produced due to the degradation of polymer chains, additives or adhesive layers. The irradiation and industrial microwave treatment was found to save cost and time and improve the quality. Glass, paper and ceramics were used for microwave packaging (Guillard et al., 2010). Significant reduction in bacterial count (*Pseudomonas fragi* and *Escherichia coli*) was achieved, when UV, laser and microwave heat treatments were applied in sequence (Maktabi, Watson, & Parton, 2011). The overall microbial reduction was higher than that of the microbial reduction achieved by the individual treatments. The order of the treatment also had significant results in such a way that the microbes were more effectively destroyed by applying laser initially then microwave and then finally UV treatment (Maktabi et al., 2011). According to the U.S. Food and Drug Administration (2000), the additional inactivation or non-thermal inactivation effect of the microwave process on microbial activation is inadequate in degree. Hence, when describing the inactivation kinetics of microwave heating, it is recommended to include only thermal effects in the model (Food and Drug Administration, 2000). However, more recently, the U.S. Food and Drug Administration has approved the microwave sterilization process for mashed potatoes in trays and salmon fillet in sauce in pouches (Brody, 2012). The process involves immersing the packaging food in pressurized hot water and simultaneously heating with microwaves at a frequency of 915 MHz and this technology was developed in Washington State University. This results in the elimination of food pathogens and spoilage microorganisms in 5 to 8 min and produces safe food with high quality.

Thus, microwave pasteurization of solid food products has some advantages over conventional treatment in terms of duration, whereas other novel techniques may also need to be combined to obtain the optimal process sequence.

6. Modeling of microwave–food interactions

Modeling of microwave heating involves the use of electromagnetic equations and energy equations to predict the temperature distribution as well as microwave power absorption inside the food products. Lambert's law and Maxwell's field equations are generally used as electromagnetic equations to describe microwave absorption. Lambert's law is based on the exponential decay of microwave absorption within the product. As Lambert's law is limited to semi-infinite samples, this law leads to a poor approximation for various practical situations. On the other hand, Maxwell's equations provide an exact solution for the propagation of microwave radiation within the samples. The Maxwell's equations which govern the propagation of microwave radiation in a dielectric medium are given by

$$\nabla.\boldsymbol{D} = \nabla.(\varepsilon * \boldsymbol{E}) = \rho \tag{6}$$

$$\nabla.\boldsymbol{B} = \nabla.(\mu \boldsymbol{H}) = 0 \tag{7}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{8}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \tag{9}$$

where **H** and **E** are the magnetic and electric field intensities respectively; **J** and $\frac{\partial \boldsymbol{D}}{\partial t}$ denote the current density and displacement current density, respectively; **D** and **B** signify the electric flux density and magnetic flux density respectively; μ is the magnetic permeability; and ε^* is the permittivity; ρ is the density of the food material and t is the time required for heating. Note that, **D**, **B**, **J**, **H** and **E** are vector quantities whereas ε^*, μ, and ρ are scalar quantities.

During microwave heating, the dielectric properties of the food sample vary significantly with change in the temperature. Hence the combination of electromagnetic equations and the energy equations is necessary to predict the temperature distributions. The governing energy balance equation for microwave heating of food samples in which the heat transport occurs due to conduction and convection is given as

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u(\nabla \cdot T) = \nabla \cdot (k \nabla T) + q(x, T) - h_{fg} \dot{I} \tag{10}$$

where C_p is the specific heat, u is the fluid velocity, k is the thermal conductivity, T is the temperature, x is the spatial distance and q is the rate of heat generation, which is given by Eq. (4) (Chandrasekaran, Ramanathan, & Basak, 2012; Datta & Anantheswaran, 2000). In Eq. (10), the first and second terms on the left hand side represent rate of accumulation of heat energy and convective energy flow, respectively. $h_{fg}\dot{I}$ is the energy used in the internal evaporation in which h_{fg} is the latent heat of vaporization and $\dot{I}$ is the volumetric evaporation term (Datta & Anantheswaran, 2000). Convective heat transport plays a major role in microwave heating of liquid samples as well as porous food materials containing liquid and vapor. In microwave heating, the temperature distribution depends upon various factors such as internal diffusion, surface heat transfer and the rate of heat generation. Since, the dielectric properties of food sample vary with food composition, temperature, size and shape, the value of q also varies accordingly (Datta & Anantheswaran, 2000).

The boundary condition leading to the convective and radiative heat transfer from the boundaries of the sample to the surrounding is given by,

$$\boldsymbol{n} \cdot k \nabla T = h(T - T_\infty) + \sigma_h \varepsilon_h \left(T^4 - T_\infty^4\right) \tag{11}$$

where $\mathbf{n}$ is the outward pointing unit normal on the surface of the sample, T_∞ is the ambient temperature, h is the heat transfer coefficient, ε_h is the emissivity of the sample and σ_h is the Stefan Boltzmann constant (Chandrasekaran et al., 2012; Datta & Anantheswaran, 2000). The combined electromagnetic equation and energy equations involving microwave heat and moisture transport can be solved either by finite difference time domain method (FDTD) or by finite element method (FEM) (Datta & Anantheswaran, 2000).

6.1. Modeling of microwave–food interactions—applications

Microwave heating of solid food with rectangular and cylindrical geometries were theoretically investigated by Lin, Anantheswaran, and Puri (1995). Lambert's law was used to determine the temperature distribution and microwave power absorption during microwave heating of solid foods and the equations were solved using two dimensional finite element software. The model predictions were validated using sodium alginate gel and the results showed that the model predictions were in good agreement with the rectangular shaped samples. For cylindrical samples, the temperature distribution predicted by the model was similar at all regions, except at the central region. The difference in the temperature distribution might be due to the changes in thermal diffusivity, attenuation factor and microwave power output during microwave heating of the samples (Lin et al., 1995). Similarly, a software utilizing three dimensional finite element method was used to predict the temperature and moisture distributions during microwave heating of cylindrical and slab-shaped potato specimens (Zhou, Puri, Anantheswaran, & Yeh, 1995). For slab sized potatoes, the predicted temperature and moisture distribution were found to vary slightly with the measured values. The difference in measured temperature values might be due to the insufficient accuracy of the thermocouple probe location, the measured surface evaporation rate and the absorbed power and non-uniform power distribution. The difference in measured moisture distribution might be due to the initial moisture loss before microwave heating, non-uniform moisture content distribution of potato samples and non-uniform microwave power distribution (Zhou et al., 1995).

The temperature distribution in 2% agar gel cylinders using pulsed and continuous microwave heating were predicted using Lambert's law and Maxwell's equations (Yang & Gunasekaran, 2004). The temperature predictions provided by the Maxwell's equations were more accurate than that of Lambert's law equation. This is due to the fact that Maxwell's equations consider standing wave effect inside the sample whereas Lambert's law does not account for standing wave effect, due to the assumption of semi-infinite sample length of materials. Maxwell's equations predicted an oscillating pattern for continuous microwave heating of samples whereas for pulsed microwave heating smooth curves were predicted. At pulsed microwave heating, thermal diffusion occurs during power-off period and thus the oscillation caused during power-on period was compensated. Hence, better temperature uniformity and substantial reduction in hot spots were found to be observed during pulsed microwave heating than that of continuous microwave heating (Yang & Gunasekaran, 2004). Further, a simulation model was developed to optimize pulsed microwave heating of precooked mashed potato cylinders (Gunasekaran & Yang, 2007). The results showed that the uniform and efficient heating was achieved for samples having a radius in the range of 2.4–2.8 cm. (Gunasekaran & Yang, 2007). Boldor, Sanders, Swartzel, and Farkas (2005) developed a heat and mass transfer model for continuous drying of peanuts in a planar microwave field. Transport equations were developed for the batch-type microwave drying in order to determine the spatial variation of the electric field. It was found that, for the same moisture content of peanuts, the temperature profiles were affected by microwave power level only. The temperature profiles predicted by the model matched with the temperature measured using fiber optic temperature probes inserted into peanut pods. On the other hand, exact theoretical determination of moisture content reduction was not possible due to the varying dielectric properties of the sample with respect to the moisture content (Boldor et al., 2005).

Geedipalli, Rakesh, and Datta (2007) developed a computational model involving Maxwell's equation to determine the heating uniformity of food kept in a microwave oven. Fig. 4 shows the temperature contours of microwave heated food samples with and without the rotation of the carousel. The presence of a rotating table or carousel improved the heating uniformity in the radial direction. On the other hand, the heating uniformity varied across the axis of the rotation due to no change in the electromagnetic radiation along the axis. Also, the temperature contours of the rotated food were more evenly distributed compared to those of the stationary food. The rotation of the carousel was reported to increase the temperature uniformity up to 43% whereas it did not improve uniformity across the axis of the rotation (Geedipalli et al., 2007). In another study, it was determined that for symmetric microwave source, rotation of food samples lead to non-uniformity of temperatures whereas for non-uniform sources, at a controlled rotation rate, temperature uniformity can be attained (Chatterjee, Basak, & Das, 2007). It may be noted that increasing the rotating rates might lead to an increased volume of the unheated central region which can be avoided by increasing the power source intensity (Chatterjee et al., 2007). Thus, uniformity in temperature distribution can be obtained by providing a carousel with a controlled rotation rate.

Souraki and Mowla (2008) performed experimental and theoretical analysis on microwave assisted fluidized bed drying of green peas. Glass beads were used in the fluidized bed as inert energy carriers. A mathematical model based on simultaneous heat and mass transfer was proposed to predict the temperature and moisture distributions during the drying process. The predicted results were found to be in good agreement with the experimental data. The drying rate was

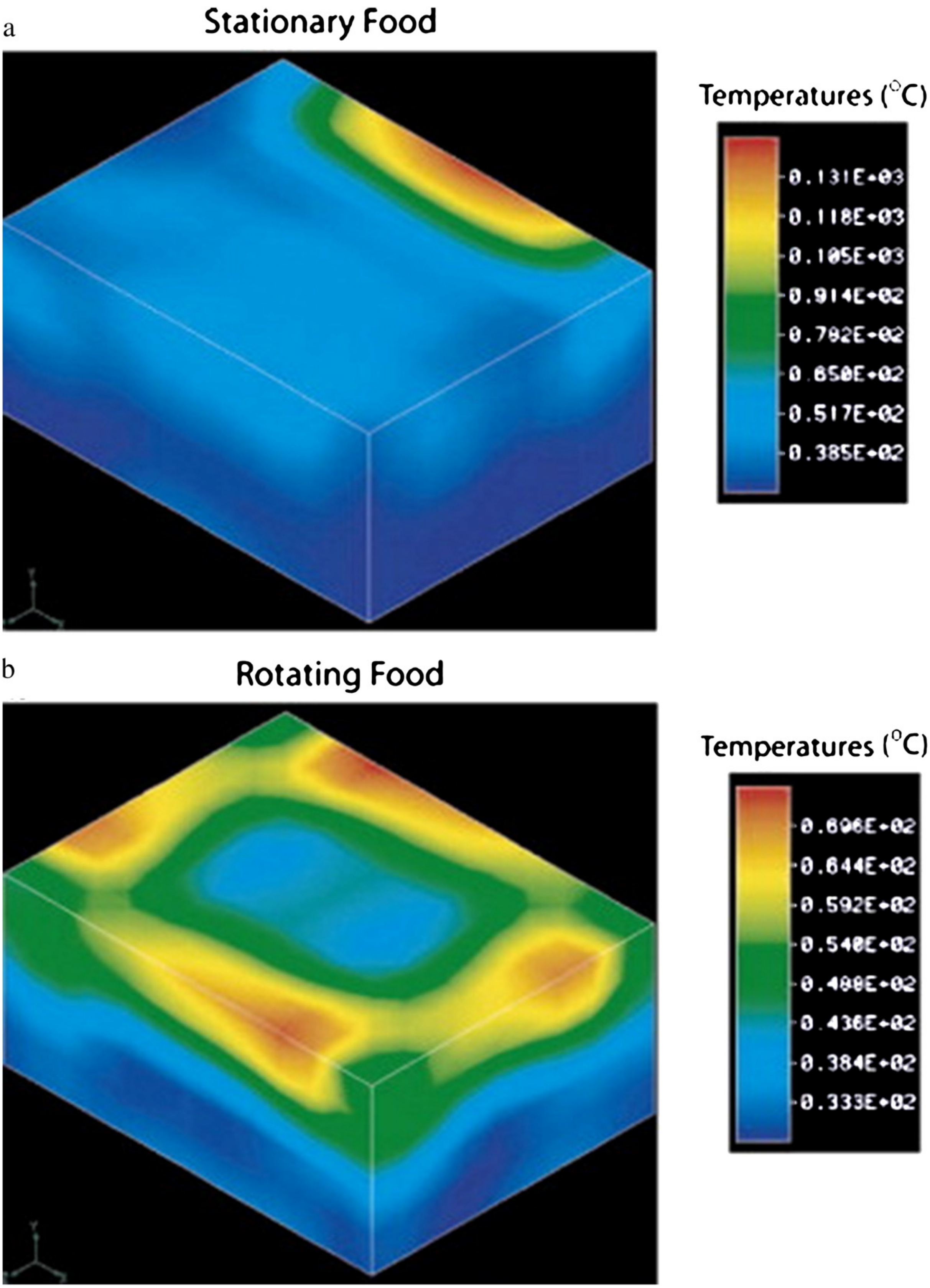

Fig. 4. Temperature contours of microwave heated food samples a) without rotation and b) with rotation of the carousel. Reproduced from Geedipalli et al. (2007), with permission from Elsevier.

higher for microwave heating, compared to pure convective heating. Due to internal heat generation, the temperature of the samples at the end of microwave drying was found to be higher than drying air temperature (Souraki & Mowla, 2008).

Knoerzer, Regier, and Schubert (2008) developed a three dimensional computational model to study the time-dependent temperature profiles of microwave treated products. The simulation is based on a user-friendly interface (MATLAB®) coupling two commercial software packages (QuickWave-3D™ and COMSOL Multiphysics™). The equations involving the electromagnetic part of the model were solved with the finite difference time domain method using QuickWave-3D™ and the heat transport equation was solved with the finite element method using COMSOL Multiphysics™. This model was able to predict hot and cold spots in the food products. Microwave heating can be optimized using this model, thus minimizing time/temperature for the process and while also attaining uniform temperature distributions. The model was validated using magnetic resonance imaging (MRI) technique (Knoerzer et al., 2008). Temperature measurements using MRI can be used for the three dimensional measurements of microwave heating patterns (Knoerzer, Regier, Hardy, Schuchmann, & Schubert, 2009). Based on MRI technique, good spatial resolution is attained for surface temperature as well as temperature distribution throughout the product (Knoerzer et al., 2009). The model predictions were in good agreement with the actual temperature measured using magnetic resonance imaging (Knoerzer et al., 2008). Malafronte et al. (2012) developed a simulation model to describe a combined convective and microwave assisted drying of potato matrix. The simulation was carried out by solving the heat and mass transfer balances (liquid-water and water-vapor) within the potato samples using a multi-physics approach (COMSOL) and the Maxwell's equations to describe electromagnetic field propagation within the waveguide. Two models, Model I for (potato samples) and Model II (for general vegetables) were proposed based on the relative permittivities at 2.45 GHz, which is a function of moisture content in the former model whereas it is a function of temperature, moisture content and ash in the latter model. It was observed that Model II provided a good agreement between experimental data and simulated profiles up to 270 s and deviated thereafter. On the other hand, the simulated profiles of 'Model I' did not match with the experimental data which suggest that other factors such as temperature and ash in addition to moisture content are necessary to determine relative permittivities to satisfactorily predict thermal profiles during microwave heating of samples (Malafronte et al., 2012).

Chen, Tang, and Liu (2008) developed a numerical model to determine the electromagnetic and thermal field distributions in moving food packages containing whey protein gel. The packaged foods were moved along circulating water which is maintained above 120 °C in the pressurized microwave cavities. Based on simulation studies, they were able to identify the regions where microwave energy was more focused and the regions where microwave energy was not focused (Chen et al., 2008). In another study, a coupled electromagnetic–heat transfer model consisting of Maxwell equations and heat transfer equations were proposed for various combinations of heating modes such as microwaves, convection and radiant heating (Rakesh, Seo, Datta, McCarthy, & McCarthy, 2010). The model was solved by finite element method (FEM) using COMSOL package and was validated using MRI techniques. It was reported that the predicted temperatures agreed well with the experimental results (Rakesh et al., 2010). Similarly, the temperature distributions in continuous flow microwave heating of Newtonian as well as non-Newtonian fluids was simulated by combining electromagnetism, fluid flow and heat transport in COMSOL Multiphysics (Salvi, Boldor, Aita, & Sabliov, 2011). The predicted data were validated using CMC solution and tap water and the results showed that the differences in predicted data can be reduced by decreasing the mesh size in the simulations (Salvi et al., 2011). Microwave heating in domestic ovens was simulated by coupling electromagnetic equations and heat transfer equation (Pitchai, Birla, Subbiah, Jones, & Thippareddi, 2012). The equations were solved using finite difference time domain (FDTD) based commercial software (Quickwave v7.5). Scattering parameter which is a measure of reflected power to the magnetron power from the cavity was calculated. The reflected power was slightly higher for the TE_{10} mode compared to that of the TEM mode at the frequency range of 2.4–2.5 GHz. This indicates that the microwave energy couples well with the TEM mode than that with the TE_{10} mode (Pitchai et al., 2012).

6.2. Microwave heating of food materials using supports

Basak and Meenakshi (2006a) carried out a detailed theoretical analysis on microwave heating of food slabs which are placed on ceramic plates (alumina and SiC). The effects of various distributions of microwave incidence (one side or two side incidences) were studied for low and high dielectric food materials such as beef and oil. For food materials attached with ceramic plates, one side or both side incidences might be preferred. It was found that without ceramic support, one side incidence caused high heating rates for the beef samples whereas the heating rate of oil remain unchanged for various types of incidences. Thermal runaway was found to be predominant for beef samples attached with the SiC plates whereas heating of oil samples by equi-distributed microwave incidence exhibited smaller thermal runaway (Basak & Meenakshi, 2006a). Alumina support was preferred for oil samples directly exposed to microwaves whereas alumina or SiC supports can be used for beef layer and oil–beef layers exposed to microwaves. For distributed microwave incidences thermal runaway could occur for alumina supported samples whereas thermal runaway can be reduced with the help of SiC supports (Basak & Meenakshi, 2006b). The heating rate of beef samples could be enhanced with the help of metallic support (Basak, 2007). For smaller oil thicknesses on beef samples, the combined metallic–ceramic composite support provided higher heating rates compared to sole effects of metallic or ceramic support only (Basak, 2007).

Durairaj and Basak (2009) carried out theoretical analysis on microwave heating of discrete beef and bread samples with alumina or SiC placed as an intermediate layer. They found that the power absorption and the temperature distributions were functions of microwave incidence type, food sample ratio, type of ceramic material used and its thickness. For the discrete beef sample, alumina as the intermediate layer provided higher power absorption than SiC intermediate, whereas for discrete bread samples, SiC as the intermediate layer showed higher power absorption than alumina intermediates. For bread samples, power enhancement was lesser and thermal runaway was larger compared to that of beef samples (Durairaj & Basak, 2009; Durairaj, Chaudhary, & Basak, 2009). Microwave heating of pork meat samples (Pork Luncheon Roll and White Pudding) supported on ceramic plates (alumina or SiC) showed that the time required for processing PLR samples with one/both microwave incidences was found to be higher compared to that of WP samples (Basak & Rao, 2010). It was reported that pulsed microwave heating reduced the formation of hot spots within the samples. The degree of thermal runaway in the absence of pulsing was found to be lesser during distributed microwave incidence and hence the processing time was found to be reduced for both the samples (Basak & Rao, 2010). In another study, the efficient heating strategy of intermediate ceramic layers placed in between pork meat samples was investigated (Basak & Rao, 2011). For low thickness samples in the presence of one side incidence, an increase in the thickness of the intermediate ceramic layers resulted in a decrease in the processing time. But, for both side incidences, the processing time was found to increase with an increase in the thickness of the intermediate alumina layer (Basak & Rao, 2011).

Simulation of microwave heating of oil–water emulsions (oil in water and water in oil) was also carried out using various supports such as ceramic or metallic or combination of both supports (Samanta & Basak, 2008, 2009, 2010; Samanta, Basak, & Sengupta, 2008). The results showed that the microwave power absorption was found to be higher for both o/w and w/o emulsion slabs supported in alumina plates than samples supported in SiC plates (Samanta & Basak, 2008). The microwave power absorption of oil–water samples could be enhanced when the samples were supported with metallic or ceramic–metallic composites. It was concluded that SiC–metallic support might be favored for o/w samples with high oil fractions whereas for samples with small fractions, metallic as well as alumina–metallic supports were recommended (Samanta & Basak, 2008; Samanta et al., 2008).

6.3. Maxwell's equations: closed form solutions

Bhattacharya and Basak (2006a) carried out closed form analysis on microwave power absorption and its heating characteristics during microwave processing of food materials such as 2% agar gel, potato, beef and marinated shrimp. The absorbed power distribution can be distinguished into three regimes based on the sample length and dielectric properties of a material: thin, resonating and thick sample regimes. In thin samples, the power distribution is almost uniform whereas in thick samples, the absorbed power distribution is exponential in nature (Bhattacharya & Basak, 2006a, 2006b). The resonating samples lie between thin and thick sample regimes in which power distributions exhibit spatial oscillation. It was reported that the uniform spatial temperature occurs for food materials with thin sample limit whereas hot spots occur at the surface of the food materials with thick sample limits (Bhattacharya & Basak, 2006a, 2006b). However, hot spots in food materials may be controlled with the distributed microwave incidence. The closed form analysis was found to be useful in determining suitable sample thickness with various microwave power distributions and thus an efficient thermal processing of food can be predicted (Bhattacharya & Basak, 2006a, 2006b). Boillereaux, Alamir, Curet, Rouaud, and Bellemain (2011) estimated the temperature distribution during microwave tempering of foodstuffs for which dielectric properties are unknown. A generic software sensor CLPP (Capteurs Logiciels Plug & Play) is used for estimating the internal temperatures and dielectric properties. The software is based on a model originating from the closed-form solutions of Maxwell's equations which is coupled with the heat conduction equation. In microwave tempering of frozen beef samples with known electromagnetic properties, the estimated profile using CLPP coincide with the simulated profile obtained from the numerical solution of Maxwell's equation. Hence the software can be used to measure internal temperatures of samples with poorly known dielectric properties (Boillereaux et al., 2011).

6.4. Microwave heating of porous media

A porous medium is a solid having pores which is filled with either gas or liquid. These pores are interconnected with each other so that heat and mass transfer occurs through them (Datta, 2007a). In capillary porous materials the pore diameter is less than 10^{-7} and hence the transport of water is more complex than non-porous materials. Water transport in porous materials might occur due to molecular diffusion, capillary diffusion and convection. In developing a porous model, heat and mass transport in porous medium as well as shrinkage or deformation of the medium is coupled (Datta, 2007a). Ni, Datta, and Torrance (1999) developed a multiphase porous media model to predict the moisture transport during intensive microwave heating of biomaterials. It was found that the moisture accumulation on the surface was high, since the rate of moisture transport from inside was higher than the rate of moisture removal from the surface. Hence, in order to remove moisture from the surface, it was recommended to combine microwave with hot air and/or infrared heating (Datta, 2007b; Ni et al., 1999). The closed form solutions of Maxwell's equations can be used to predict temperature distribution where dielectric properties are barely known. Based on certain threshold power level of infrared, the surface moisture can be reduced to less than its initial value (Datta & Ni, 2002). However, below a threshold power level, infrared heating results in the surface moisture build-up. The rate of surface moisture removal by hot air was not as efficient as infrared heating which might be due to the lower surface heat flux compared to infrared energy. On the other hand increasing the air velocity might increase the heat and mass transfer coefficients and hence surface moisture could be greatly reduced (Datta & Ni, 2002). Apart from food applications, microwave heating of porous media could be helpful for soil remediation which is contaminated with volatile organic compounds through microwave induced steam distillation (Acierno, Barba, & d'Amore, 2003). Since dry soil is a weak absorber of microwaves, soil–water mixtures have a significant loss factor to absorb microwave energy. As the dielectric properties of the soil matrix changes with an increase in temperature, the soil becomes hotter and dryer and allows microwave to pass through easily. The generated vapor flux move toward the surface of the soil, thus carrying pollutant substances out of the matrix. A predictive model has been developed to predict temperature, humidity and relative permittivities of the soil during microwave treatment and it was found that the model predictions agreed well with the experimental results (Acierno et al., 2003). Recent applications include, microwave regeneration of a soot trap ceramic filter which is used to clean the exhaust of industrial diesel engines (Barba, Acierno, & d'Amore, 2012). With the help of microwave assisted combustion, the soot oxidation is induced without thermally stressing the ceramic matrix. Since carbon is a strong absorber of microwaves, it dissipates microwave energy into heat and reaches combustion temperature. Due to low thermal conductivity of ceramics and relatively fast soot oxidation, the ceramic matrix is kept cool and regenerated. A mathematical model was developed based on the heat and mass transfer and Maxwell's equations to predict the development of combustion stages and the performance of the remediation. It was observed that the model predictions satisfactorily agree with the experimental results (Acierno, Barba, & d' Amore, 2004; Barba et al., 2012). The loss factor plays a crucial role in determining the heating rate as well as induced thermal gradients during microwave heating processes (Acierno et al., 2004). By combining small amounts of strong microwave absorbers with weak loss materials, the thermal gradient of a low conducting material could be improved (Acierno et al., 2004).

Microwave heating of porous beef (beef–air and beef–oil) samples of different porosities (0.3, 0.45 and 0.6) were carried out with and without ceramic supports (Al_2O_3 and SiC) (Basak, Aparna, Meenakshi, & Balakrishnan, 2006). The results showed that the microwave power absorption of porous beef was found to decrease porosity as, pure beef exhibits higher average power absorption than porous beef does. The average power absorption was also found to be more enhanced for porous beef samples in the presence of alumina support than in the presence of SiC support. An increase in the porosity increases the thermal runaway of beef–air samples whereas beef–oil samples exhibited low thermal runaway at all porosities (Basak et al., 2006). In another study, the heating efficiency of porous beef samples was found to be enhanced with the ceramic–metallic supports. Moreover, samples attached with ceramic supports (alumina and SiC) had lesser power absorption compared to samples attached with composite supports (alumina–metallic and SiC–metallic). This is due to the fact that metallic supports reflect microwaves and causes stronger stationary waves within the sample. Hence, the power absorption of samples attached with metallic support was found to be higher compared to that of samples attached to the ceramic supports (Aparna, Basak, & Balakrishnan, 2007). Thus, with the help of modeling and simulations, the temperature and moisture distributions during microwave heating of various food materials can be predicted and the results will be useful for the design of microwave food processing.

7. Concluding remarks and future scope

Microwaves have been successfully used for many food processes such as cooking, drying and pasteurization of food materials. In this article, experimental investigations on various microwave assisted food processing techniques and modeling of microwave heating of food materials were reviewed. Knowledge of dielectric properties is very helpful for designing a microwave oven. Non-uniform temperature distribution during microwave heating was found to be affected by the shape, size and position of a food material. In general, the center region of a food material generated more hot spots than at other regions.

Microwave cooking is affected by the presence of moisture and fat content in food materials. Microwave cooked products have the advantages of retaining more taste, color, quality and nutritional value compared to those cooked by other conventional methods. Microwave pasteurization was found to be more effective in the destruction of pathogens or in the inactivation of enzyme, due to significant enhancement or magnification of thermal effects.

Microwave combined with other drying methods such as air drying or infrared or vacuum drying or freeze drying gave better drying characteristics compared to their respective drying methods or microwave drying alone. Modeling of microwave heating of food materials by the combination of electromagnetic equations (Maxwell's equations or Lambert's law equations) as well as heat and mass transport equations were used to predict temperature and moisture distribution during microwave heating of food materials. The applications include microwave heating of food materials using supports and microwave heating of porous media.

Although microwave energy has wide application and uses in various food processes, it needs significant research aimed at improvements in certain areas. Specifically, methods to obtain final food products with better sensorial and nutritional qualities need to be explored. Improving the energy efficiency in rice cooking and obtaining good quality product in bread baking are examples of other potentially challenging areas. Microwave processing of food materials needs to be carried out to a great extent at a pilot scale level than at laboratory conditions so that the results might be useful for industrial applications. In spite of the complex nature of microwave–food interactions, more research needs to be carried out for a better understanding of the process.

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