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Review
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Review

Critical review of radio-frequency (RF) heating applications in food processing

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Abstract

Conventional thermal treatment in food processing relies on the transfer of heat by conduction and convection. One alternative to this conventional thermal treatment is radio-frequency (RF) heating in which electromagnetic energy is transferred directly to the heated product. The longer wavelengths of RF compared with microwaves are able to penetrate further into the food products resulting in more even heating. A review of RF heating for the food processing industry is presented here with an emphasis on scientific principles and the advantages and applications of RF. Applications of RF heating include blanching, thawing, drying, and processing of foods. RF heating represents considerable potential for additional research and the transfer of technology to the food processing industry. Computer simulation can be used to improve RF heating uniformity. Moreover, the heating uniformity in the rotated eggs is greater than in the static eggs. RF has also been used to blanch vegetables to increase ascorbic acid content to achieve the highest vitamin C levels. The use of the thawing technology has resulted in better quality of treated food. There has been increased interest in the RF-drying method due to the homogeneity of heating, greater penetration depth, and more stable control of the product temperature. RF-treated meat had improved quality and coagulation with acceptable taste and appearance. In addition, RF heating is used in pasteurization of yogurt and destruction of microorganisms in liquid and solid foods.

Key words: heating; radio frequency; non-thermal; dielectric properties.

Introduction

Thermal treatment is a very common method in food processing industries to eliminate microorganisms and inhibit the activity of harmful enzymes in order to ensure the safety of food products and extend product shelf life. Thermal treatment involves the transfer of heat through conduction and convection, which can prolong the time required for heating depending on the food matrix. These restrictions can lead to significant physiochemical changes within thermally treated food products which can result in alterations in sensory and textile properties and can also lead to a decrease in nutritional value (Siefarth et al., 2014).

Researchers have been searching for alternative technologies to traditional thermal treatment. Over the past few decades, new technologies have been described in scientific publications, but most of these new methods have not yet been utilized in food processing industries. The use of radio frequency (RF; between 10 and 50 MHz) is one of the most important and promising modern heating techniques. RF as a heat source was first described in the middle of the 20th century and was used to melt frozen foods and to process and preserve meat products (Sanders, 1966). Electromagnetic heating is characterized by its ability to generate heat inside the food material by polarizing the guidance of polar diodes such as water or forced movement of ions. In this way, limits imposed by conventional heating are overcome. The electromagnetic heating process is relatively quick and takes place through the transmission of electromagnetic energy directly to the product. The heat is generated within the product without the need for heat transference, in contrast to conventional heating (Datta and Davidson, 2000).

Microwave heating has also been used in the manufacture of food products. This heating method improves the sensory, chemical, and physical properties of food material exposed to electromagnetic waves compared with conventional heating. However, researchers have found that frequencies used in microwave technology at about 2.45 kHz have a limited ability to penetrate larger food volume. For example, the penetration depth was measured at 1 cm for microwaves at 2.35 kHz in milk or yogurt products, whereas Felke et al. (2009) showed that the penetration depth was about 20 cm when using RFs at 27.12 MHz which resulted in the heating being more consistent for the food material, and the affected diameter was greater. Previous studies have shown that longer wavelengths used in radio-frequency heating (RF-H) do not result in any interference or negative effects inside the food, whereas the use of microwaves has led to patterns of cold and hot spots inside the food items (Piyasena et al., 2003). This review will thus present general details regarding the scientific principle of RF-H and applications of RF-H to food processing.

The scientific principle of RF-H

RF is electromagnetic waves in the range of 10 to 300 GHz (Orfeuil, 1987) as illustrated in Figure 1, but the range of frequencies used for industrial heating lies between 10 and 50 MHz (Tang et al., 2005). In addition, the permitted frequencies for medical, scientific, and industrial applications are 13.56, 27.12, and 40.68 MHz, respectively (Marra et al., 2008). Shorter wavelengths are associated with higher frequencies as illustrated in the following equation (Awuah et al., 2015):

$$c = \lambda f, \tag{1}$$

where f is the frequency of the electromagnetic wave (Hz), λ is the wavelength (m), and c is the speed of light (m/s) ($c = 3 \times 10^8$ m/s). RF has a lower frequency and longer wavelength (Figure 1) and includes the radar range.

RF is also referred to as dielectric loss heating and dielectric heating. RF-H is classified as a novel thermal processing method in the field of food engineering (Jiao et al., 2011). Since the electrical insulators of food materials are limited, the electrical energy is dissipated and stored by food when placed in an electromagnetic field. Maxwell wave equations are used to describe the absorption of this energy. The bound water in food plays an important role in dielectric heating in the frequency range between 20 and 30 000 MHz (Wang et al., 2003).

The relative complex permittivity is calculated using the following equation:

$$\varepsilon^* = \frac{\varepsilon}{\varepsilon_o}, \tag{2}$$

where ε^* is the relative complex permittivity, a composite of dielectric constant(ε), and ε_o is the free space permittivity equal to 8.8542×10^{-12} F/m.

These factors are responsible for dielectric heating. The dielectric constant is an important factor that is used for measuring the ability of food to store electromagnetic energy and thus a measure of the property of a food material to dissipate electromagnetic energy. Equation (2) describes the relationship between the relative complex permittivity, dielectric loss factor, and the dielectric constant,

$$\varepsilon^* = \varepsilon - j\varepsilon'', \tag{3}$$

where $j = \sqrt{-1}$ and ε'' is the dielectric loss factor.

To describe the dissipation factor (dissipation power) of a material, the loss tangent is used as follows (Piyasena et al., 2003):

$$tan\delta = \frac{\varepsilon''}{\varepsilon} \tag{4}$$

When foods (having polar molecules such as water) are exposed to an alternating electric field, dielectric heating occurs. The polar molecules have electric dipole moments, and the negative and positive charge centres do not align when food is placed in an electric field and polar molecules align to the electric field. Polarization occurs due to the migration of positive and negative charges to the different ends of the molecules (Figure 2). Polar molecules also rotate continuously to align with the changing field within an alternating electric field. This process is called dipole rotation (Marra et al., 2008). During this process, the friction among molecules converts electromagnetic energy into heat, so the temperature of treated materials rises. However, the motion of dissociative ions in foods corresponding to an applied alternating electric field is in the same

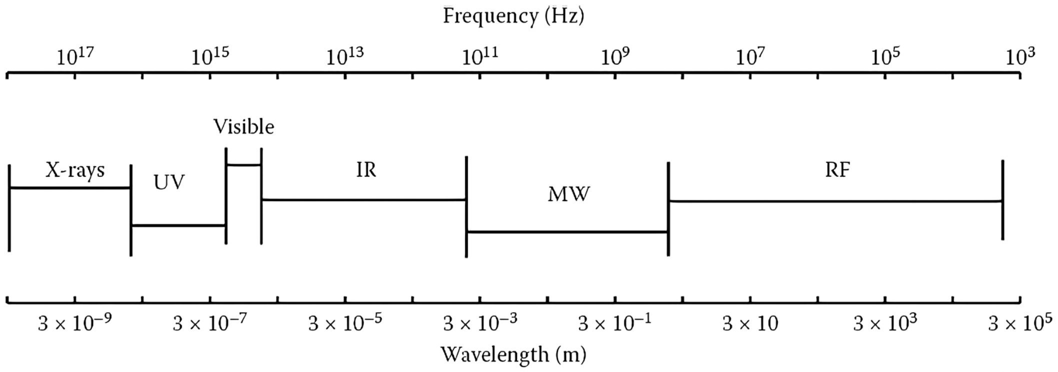

Figure 1. Electromagnetic spectrum adapted from Marra, et al.(2008).

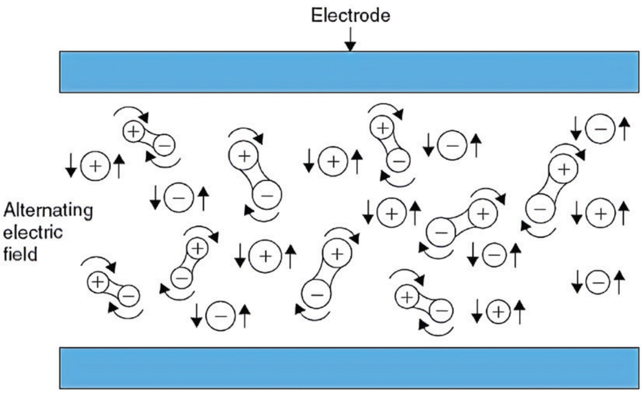

Figure 2. Space charge and dipolar polarization in an alternating electric field at radio frequencies, adapted from (Orsat and Raghavan, 2005).

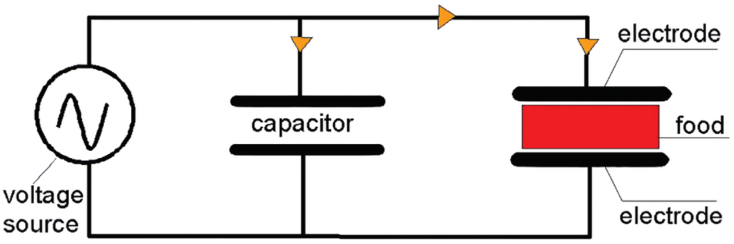

Figure 3. Schematic diagram of a radio-frequency heating (RF-H) system.

direction. Consequently, the oscillating motion of ions (forward and backward) in the material generates heat due to friction (Buffler, 1993). This mechanism is known as ionic conduction. Dipole rotation and ionic conduction are the primary dominant techniques in RF-H (Ryynanen, 1995). Temperature and frequency play an important role in both of these mechanisms due to an increase in the movement of molecules by increasing frequency and temperature. A RF-H system consists of an alternating voltage source, capacitor, and two electrodes, all of which are connected to form an electric circuit for a dielectric heating system as shown in Figure 3.

The capacitance of the capacitor can be calculated by the following equation:

$$C = \frac{\varepsilon\, \varepsilon_O A}{d}, \tag{5}$$

where d is the distance between electrodes (m) and C is the capacitance (Farads).

The time rate of temperature increase and power dissipation in dielectric heating can be calculated from the following equations (Orsat and Raghavan, 2005):

$$\frac{dT}{dt} = 0.239 \times 10^{-6} \frac{P}{c\rho}, \tag{6}$$

$$P = 5561 f E^2 \varepsilon'' \times 10^{-12} \tag{7}$$

where $\frac{dT}{dt}$ is the time rate of temperature increase (°C/s), P is the power (W/m^3), c is the specific heat of the dielectric material (J/kg.K), ρ is the density (kg/m^3), f is the frequency (Hz), and E is the rams value of the dielectric loss factor (V/m).

Power penetration depth (d_p) was calculated as follows (Buffler, 1993):

$$d_p = \frac{c}{2\sqrt{2}\pi f \left\{\varepsilon \left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon}\right)^2} - 1\right]\right\}^{1/2}}. \tag{8}$$

Heat transfer occurs by conduction within the food, and convection at the food surface and heat generation within food happens by RF-H. Heat transfer in an electromagnetic field is calculated from the following equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla (k \nabla T) + Q, \tag{9}$$

where Q is the RF power absorption density delivered to the food at electric field intensity. Q can be calculated as (Barber, 1983)

$$Q = 2\pi f \varepsilon^o \varepsilon_r'' E^2, \tag{10}$$

where E is the electric field intensity which is governed by the electromagnetic field and affected by dielectric properties of food, $\varepsilon^o \varepsilon_r'' = \varepsilon''$, and r is the relative energy loss permittivity.
Equation (9) can be written as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\mathrm{k}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mathrm{k}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mathrm{k}\frac{\partial T}{\partial z}\right) + Q. \tag{11}$$

Heat generation is a function of moisture and temperature at specific locations x, y, and z.

Mathematical models play an important role in optimization of the product and processing parameters and design during RF-H.

Heating time is given by the following equation (Orfeuil, 1987):

$$t_h = \frac{C_p \rho \Delta T}{E^2 \omega \varepsilon''}, \tag{12}$$

$$Pv = E^2 \omega \varepsilon'', \tag{13}$$

$$\omega = 2\pi f, \tag{14}$$

where Pv is the maximum power per volume (W/m^2), ω is the angular frequency (rad/s), ρ is the medium density (kg/m^3), C_p is the specific heat of medium (J/kg.°C), and t_h is the heating time.

Advantages and disadvantages of RF-H

RF-H presents multiple characteristics compared with conventional heat transfer and heat diffusion units. It is very important that the electrodes do not contact the food directly when using RF-H units to avoid the formation of Joule heating (Ohmic heating). This technique can be applied to both liquid and solid foods. In addition, it has been shown that the wavelength of RF (11 m at 27.12 MHz) is greater than those of microwave frequencies. Moreover, because of the capacity of RF power to penetrate deeper into foods than conventional microwaves, the heat is generated inside the food and distributed evenly. It is well-documented that construction of a large-scale RF-H is easier and improves the quality of the final product. Another advantage of this eco-friendly technology is its higher energy use efficiency (Rowley, 2001).

Disadvantages of RF-H

Like the most current technologies, RF-H presented some disadvantages that are limited essentially to the reduction in power density as reported by Jones and Rowley (1997). In addition, because of its high efficiency and output quality, RF-H equipment is more expensive compared with equipment used in traditional heating systems (Jones and Rowley, 1997).

Improvement of RF-H uniformity using computer simulation

Volumetric and rapid heating occurs when RF-H is used. The RF commercial applications are limited because of non-uniformity heating (uneven temperature distribution) in the product by using RF-H (Fu, 2004). There are many other factors that have an important effect on the RF-H uniformity such as physical properties, dielectric properties, thermal properties, the distance between the treated product and electrodes, chemical properties of the medium, and engineering design of RF-H devices (Fu, 2004). Non-uniformity RF-H may cause damage to the product and package. To solve this problem, there are many methods used to improve RF-H uniformity such as placing the product into hot air, hot water, or saline water (Harraz, 2007). Birla et al. (2008) have used rotation for improving RF-H uniformity. Wang et al. (2010) and Ling et al. (2016) have used agitation and mixing of product containers between electrodes. There is another method used for improving RF-H uniformity which is called pulse mode (Hansen et al., 2006). Computer simulation can be used to enhance RF-H uniformity via development of several models for studying different factors and methods for various foods like wheat flour (Gao et al., 2018), wheat kernel (Chen et al., 2015), soybeans (Huang et al., 2015), meat (Uyar et al., 2015), and dry food (Huang et al., 2016). Computer simulation is used to understand the new test strategy, the mechanism, parameters optimization, and determination of the best conditions of RF-H treatments for specific food products (Huang et al., 2016).

The uniformity of heating within the treated food can be calculated using the following equation (Alfaifi et al., 2016):

$$UI = \frac{\frac{1}{V_{vol}} \int V_{vol} \sqrt{(T - T_{av})^2}}{T_{av} - T_{initial}}, \tag{15}$$

where V_{vol} is the food material volume (m^3), T_{av} is the average temperature (°C), T is the local temperature (°C), and the smaller value of UI refers to the best RF-H uniformity. When UI value equals to zero, the temperature distribution into food material is completely uniform.

Alfaifi et al. (2016) have used computer simulation models to improve heating uniformity of raisins treated by RF-H for insect control. The heating uniformity was improved by rounding the corners of the containers and reducing sharp edges on packages. The configuration of electrodes was modified and used forced air after RF-H. These modifications reduced the higher temperature differences of raisin to about 5°C. In addition, reducing the length of the electrode to 4 cm less than the horizontal dimension of the rectangular containers has improved heating uniformity.

Dev et al. (2012) have used the simulation of RF-H in eggshell at 27.12 MHz to study the uniformity of heating within the treated eggs and determination of locations of hot and cold spots generated due to non-uniform heating. It can be seen from Figure 4 that the heating is non-uniform due to the generation of hot and cold spots within the eggshell, because the egg closest to electrodes heats faster than the egg farther away from electrodes. Figures 4 and 5 illustrate that the non-uniformity of RF-H increased as the air gap between eggs and parallel electrodes decreased from 5 to 0.5 mm. On the other hand, the uniformity heating in the rotated eggs is greater than the static eggs as shown in Figure 6.

Applications of RF-H in food processing

Heating of bread.

One of the earliest explorations into the RF pasteurization process was reported more than 70 years ago using two kinds of bread. A portion of sliced white bread and Boston brown bread were exposed to 14 and 17 MHz in an RF unit (Cathcart et al., 1947). Forty-seven seconds were enough to raise the temperature of the sliced bread to 60°C. This sterilization had a positive impact on the preservation of both the sliced white bread and the Boston brown bread. A quality check demonstrated an absence of mould after 10 days' storage at 24°C and 29°C. More importantly, the new technology had a positive impact on bread texture. The previously dry, leathery texture of the bread was reported to be absent after RF-H, with no change in thiamine content. A year after this discovery, another study reported the ability of RF to control both *Aspegillus* and *Penicillium* in sliced bread when treated at 26 MHz (Bartholomew et al., 1948).

Blanching

RF has also been used to blanch vegetables and to limit the loss of their nutritive value. By using an RF self-excited oscillator at

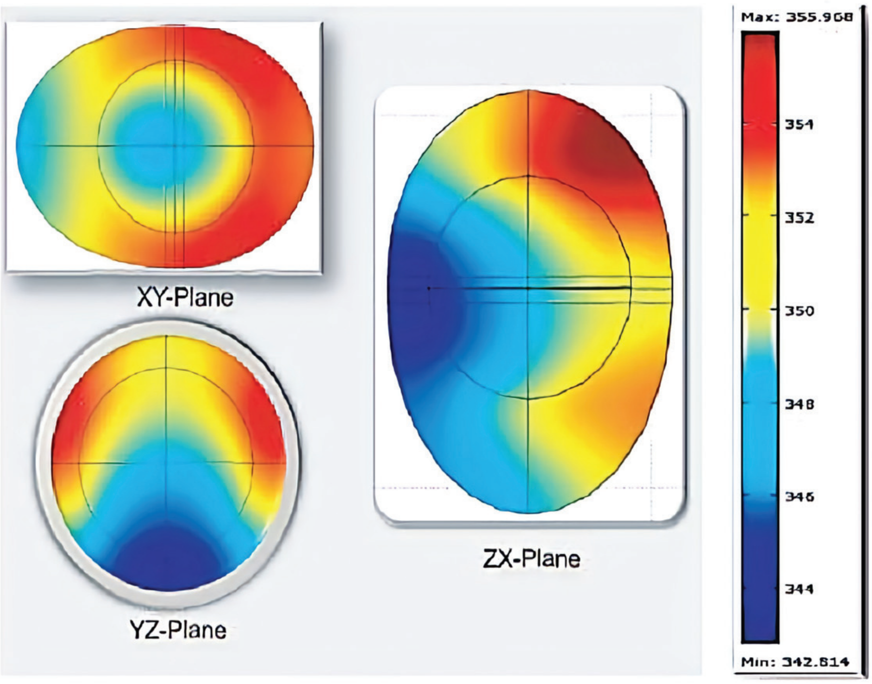

Figure 4. The simulation results of the temperature (K) distribution in the static in-shell eggs (air gap between parallel plate electrodes and eggs is 5 mm) (Dev et al., 2012).

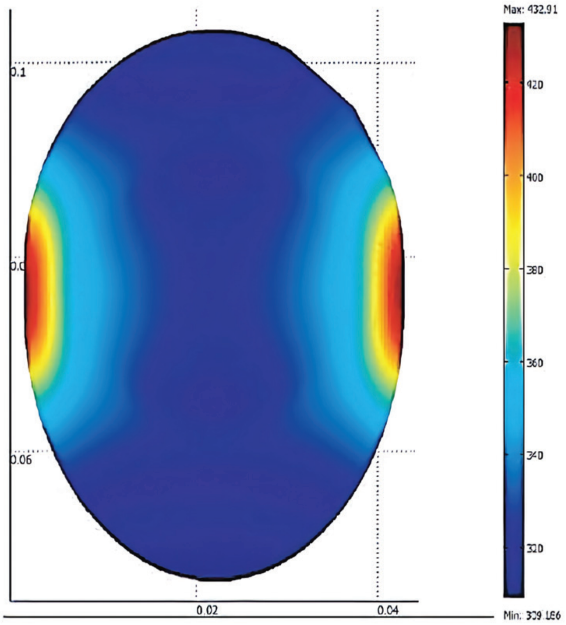

Figure 5. The simulation results of the temperature (K) distribution in the static in-shell eggs (air gap between parallel plate electrodes and eggs is 0.5 mm) (Dev et al., 2012).

15 MHz, vegetable temperature reached 77°C (Moyer and Stotz, 1947). RF-H was shown to have a negative impact on the catalase activity of the treated vegetables after a few days of storage at –23°C. Additionally, vegetables blanched at 88°C had an increase in ascorbic acid content at the highest vitamin C levels. Vitamin C is essential for the maintenance of healthy connective tissue and may also act as an antioxidant. However, it was reported that RF blanching negatively affected both vegetable flavour and color when compared with the conventional blanching method using water and steam.

Thawing

After using RF for food heating and blanching in 1947, attempts were made to use RF energy for thawing frozen products. RF at 14–17 MHz was sufficient to thaw 450 g–13.6 kg of frozen eggs, fruits, vegetables, and fish within 2 to 15 min. The use of this technology resulted in better quality due to minimal discoloration and loss of flavour when compared with traditional thawing (Cathcart et al., 1947). Fifteen years later, Jason and Sanders used RF frequencies ranging from 36 to 40 MHz to thaw white fish frozen at –29°C (Jason and Sanders, 1962). RF successfully decreased the thawing time of 3 and 16 h, when using air and water, respectively, to 12 min with RF. Using the same protocol, Sanders was able to decrease the thawing time of different food sausages, meat, pies, and bacon to 10–50 min after several passes through the RF unite (Sanders, 1966). Thawing time depends on multiple factors including the uniformity of the blocks used as well as size and dielectric properties. In general, the study demonstrated that thawing time using RF was much shorter than conventional methods.

Another independent study used 4 cm thick frozen lean beef. The heat treatment generated by an RF unit at 35 MHz required two passes though the RF unit and lasted for 34 min. Beef blocks weighing between 30 and 60 kg were thawed after 1.5 h in a 25 kW RF unit.

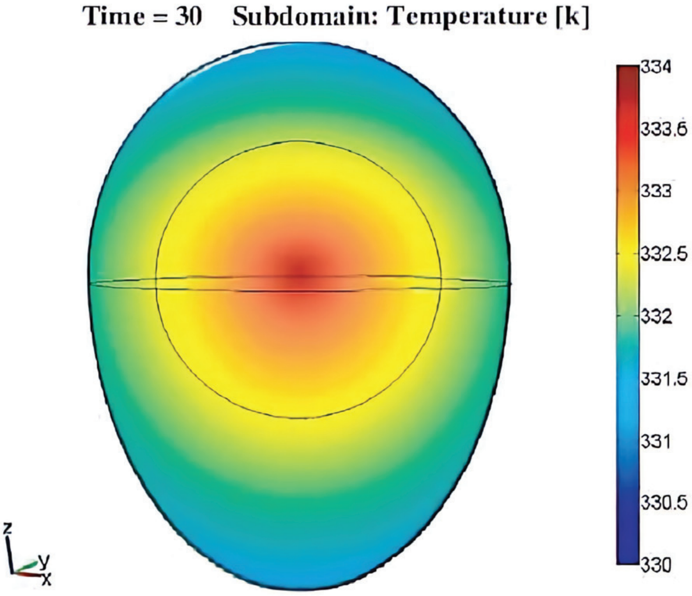

Figure 6. The simulation of temperature distribution of the rotated eggs (air gap between parallel plate electrodes and eggs is 5 mm) (Dev et al., 2012).

Drying

Drying based on RF-H offers multiple advantages over conventional drying and microwave drying (Mermelstein, 1998). For example, the Macrowave™ 7000 Series post-baking (i.e., cookies and crackers) dryer was developed by Radio Frequency, Inc. (Millis, MA) and presented multiple benefits including the following: the possibility to increase oven line speed, heat uniformity, precise power control, no temperature differential, space savings, development of desired crumb structure, and capacity to equilibrate and control moisture content resulting in a completely uniform moisture profile. RF-H was also used to sterilize packaged flour and dry food with poor thermal characteristics, such as coffee, nuts, beans, cocoa, corn, grains, and beans. A vertical RF unit at 60 MHz frequency was capable of increasing the temperature of roasting cocoa beans to 130°C, which reduced the moisture content from 6 to 1 per cent (Cresko and Anantheswaran, 1998). Because of its greater potential for penetrating to the center of the food by the emitted energy, RF-H can dry foods evenly. Figure 7 illustrates that the drying time of an RF dryer was less than that of a conventional dryer due to accelerated drying rate of the RF dryer compared with the conventional one. Drying time using the conventional dryer was 150% longer than that of the RF dryer (Awuah et al., 2015).

RF has been classified as a fourth generation drying technology (Ramaswamy, 2015). There has been increased interest in the RF-drying method due to the homogeneity of heating, greater penetration depth, and more stable control of the product temperature (Wang et al., 2014; Zhou et al., 2018). The RF-drying method is also known as dielectric heating (Zemni et al., 2017). Heating food by using RF and microwaves is faster and volumetrically efficient due to the internal heat generation in the treated food, which occurs due to ionic conductance and the dipole rotation of molecules. Food drying by RF requires less drying time and has a more uniform drying rate, and the dried food has acceptable quality (Huang et al., 2018). RF is considered a potential advanced drying method, and many researchers have used RF for drying foods such as macadamia nuts (Wang et al., 2014) and peanut kernels (Albanese et al., 2013). Zhou et al. (2018) studied the effects of three drying methods (RF, vacuum, and hot air drying) on walnut-drying characteristics as depicted in Figure 8. The time required to dry walnuts using RF was shorter than that of vacuum or hot air drying. In RF drying, the temperature increased rapidly when compared with vacuum or hot air drying because the moisture content plays an important role in the rise of treated food temperature by RF-H (9.8% dry basis). The RF-drying rate was faster than that of vacuum or hot air drying. In addition, three drying rate stages were observed (increasing, constant, and falling rate stages) with RF drying, whereas with vacuum and hot air drying, only the constant rate stage was observed.

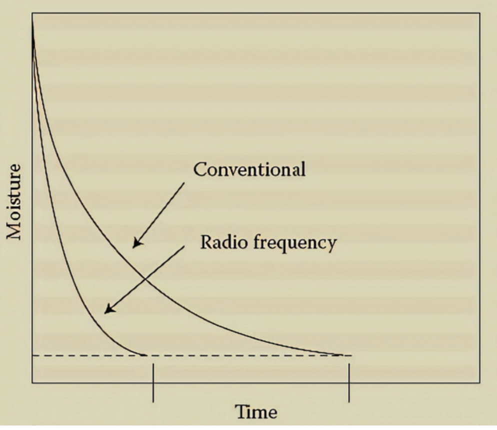

Figure 7. Typical drying curve of food materials by radio frequency (RF) and conventional dryer (Awuah et al., 2015).

Combined RF drying includes tandem and parallel drying. Tandem drying (hybrid drying) includes different drying methods at different stages in order to increase energy efficiency, thermal

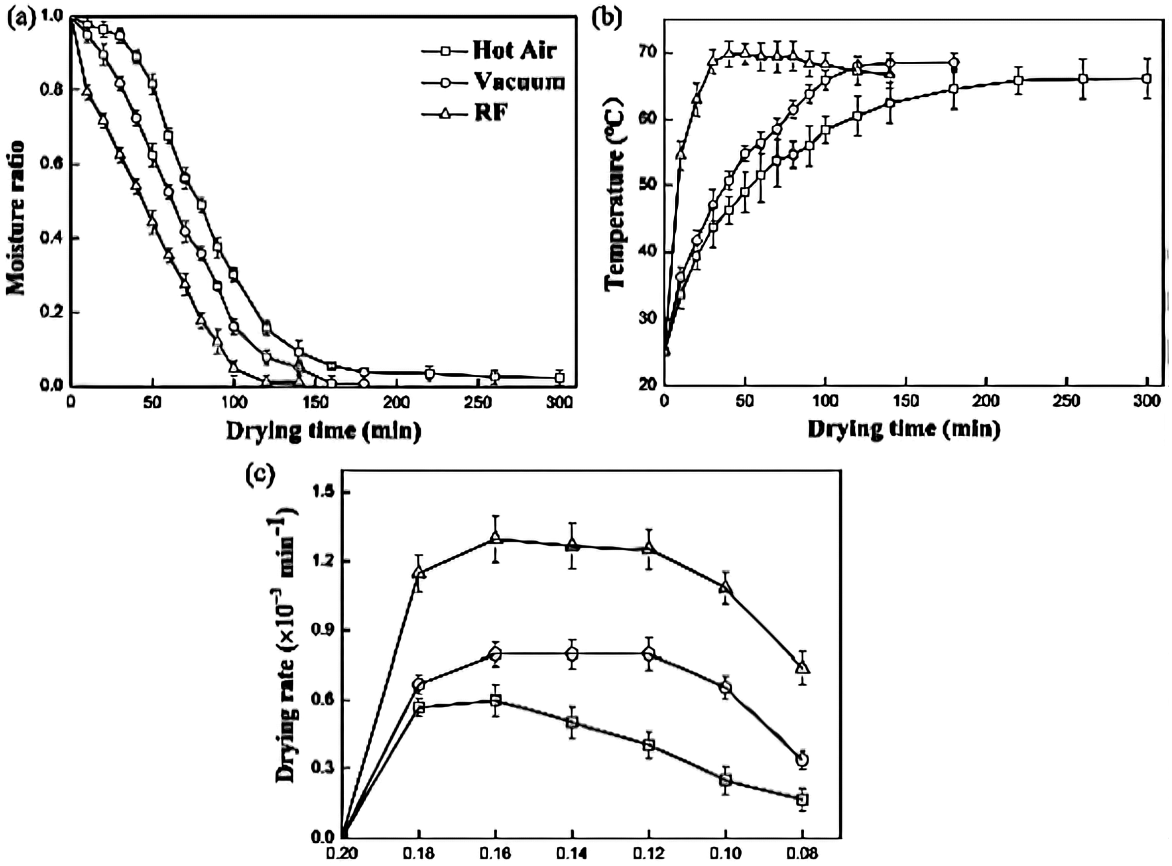

Figure 8. Drying characteristics (moisture ratio, temperature, and drying rate) of walnuts using RF, vacuum, and hot air dryers (Zhou et al., 2018).

performance, drying uniformity, and quality enhancement (Xu et al., 2004). An example of tandem drying is RF post-backing drying (Rice, 1993) which was shown to avoid discolouration and flavour loss (Koral, 2004).

The parallel-combined RF-drying method combines RF drying with a traditional drying method (vacuum, fluidized bed). The aim of parallel-combined RF drying is to increase the heat transfer by convection and conduction during drying. An example of this method is the RF vacuum dryer manufactured by Hebei Huashijiyuan Industrial 215 High Frequency Equipment, Ltd. This RF vacuum dryer consists of two electrodes (variable distance of 20–300 mm), a vacuum vessel, vacuum pump, water collector, monitoring system, and an RF-H applicator (Figure 9a). To accelerate the drying rate by convective heat transfer, RF-H is combined with hot air (Figure 9b). This system consists of parallel-perforated electrode plates, a conveyer belt, a RF-H unit, a plastic container, and a hot air system. Chickpeas, green peas, and lentils were dried using the combined RF-hot air dryer. The RF dryer decreased the heating time and decreased the heating rate for all three vegetables (Wang et al., 2010).

Meat processing

The first RF meat pasteurization studies date back to 1953. An RF unit operating at 9 MHz was able to sterilize 2.7 kg of boned ham by reaching the desired temperature of 80°C in approximately 10 min (Pircon et al., 1953). Seventeen years later, Bengtsson and Green (1970) developed continuous RF pasteurization of cured hams packaged in Cryovac casings, which was shifted from 35 to 60 MHz, reaching a temperature of 80°C at the centre of the ham. Compared with traditional hot water processing, the processing time, quality of meat, and juice losses improved significantly by using the RF unit. In addition, the RF unit required only one-third of the time for processing 0.91 kg of lean ham heated in a condenser tunnel at 60 MHz. The results showed that juice losses were reduced and quality tended to improve when compared with traditional processing with hot water (Bengtsson and Green, 1970). In 1991, a linear relationship was observed between temperature and electrode voltage used to pasteurize sausage emulsion. Two minutes were sufficient to treat sausage emulsion at a mass flow rate of 120 kg/h. When exposed to 27 MHz, the temperature increased from 15°C to 80°C. Although a conventional heating process had a heating rate of 1°C/min, an RF unit was able to treat the centre (about 50 mm diameter) of a sausage with a 40°C/min heating rate (Houben et al., 1991). RF heat treatments have exhibited a lethal effect on tested organisms at the same pasteurization values as conventional heat treatments, whereas RF-treated meat had better quality and coagulated better with acceptable taste and appearance.

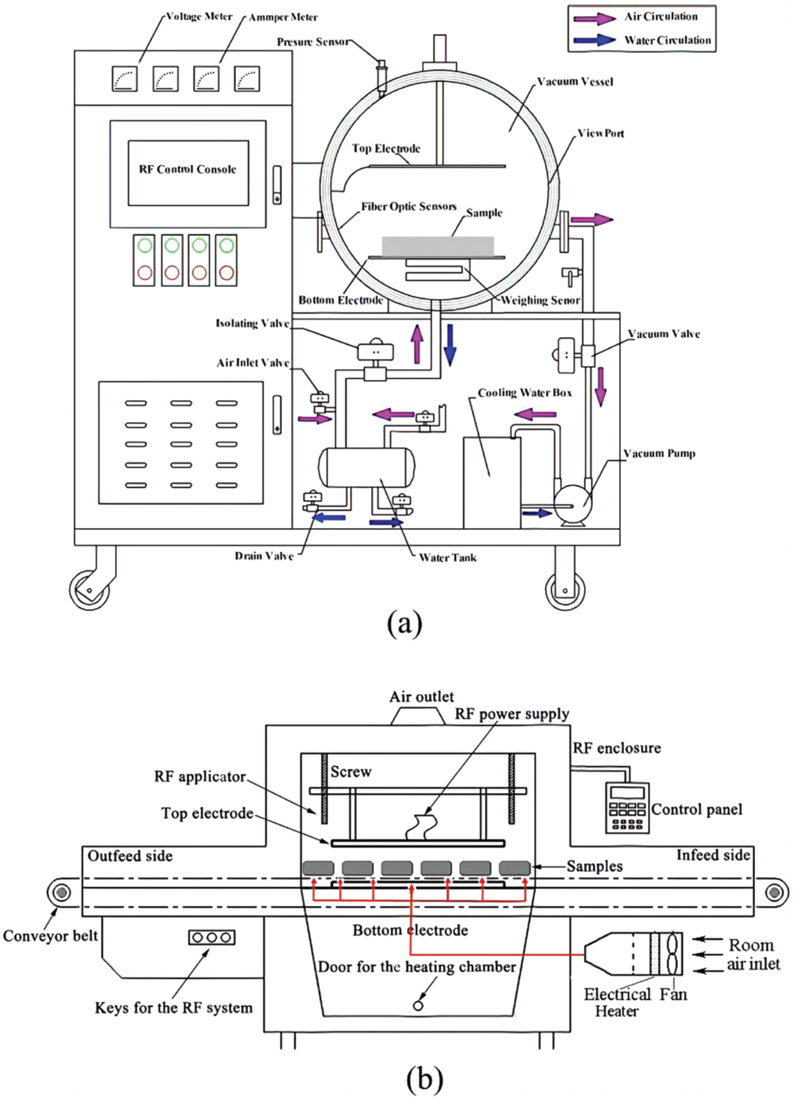

Figure 9. (a) RF-vacuum dryer and(b) RF-hot air dryer (Wang et al., 2010).

Dairy products

In a recent study, it has been demonstrated that the electrical conductivity of yogurt was directly proportional to its temperature. The reported conductivity was higher than that of milk, which could be due to the lactic acid conductivity in yogurt (Siefarth et al., 2014). When using RF-H (yogurt starting at 40°C), 60, 90, and 120 s were necessary in order to reach 58°C, 65°C, and 72°C, respectively, with a heating rate of 0.28 ± 0.02 $K \cdot s^{-1}$. Temperatures of 58°C and 65°C were consistently applied to stir yogurt in an RF water bath. However, heating yogurt jars at very high temperatures such as 72°C could cause significant overheating followed by a strong contraction of the yogurt curd and whey separation (Siefarth et al., 2014). When the same temperatures (58°C, 65°C, and 72°C) were applied to stirred yogurt in a convection oven, heat transfer limitations were observed, unlike RF-H. The convection oven heating rate was 0.30, 0.41, and 0.55 $K \cdot min^{-1}$, which was comparatively lower when compared with the heating rate of RF-H (0.28 ± 0.02 $K \cdot s^{-1}$). The heat curve showed a slowly ascending sigmoidal behaviour. Although heating was successfully applied at most temperatures, some problems were reported for the dielectric heating of yogurt gels at 72°C (Figure 10). To date, most ongoing studies aim to extend yogurt shelf life while maintaining high-product quality including texture and sensorial properties.

Effects of RF-H on inactivating microorganisms

RF-H can be used to control pathogen in foods because of fast and volumetric heating, as well as reducing loss in food quality (Hou et al., 2016). Using RF-H leads to the reduction of pathogen in agriculture materials by 4 log (Jiao et al., 2016; Li et al., 2017). Some studies mentioned that RF-H possessed the ability to inactivate *Bacillus cereus* and *Clostridium perfringens* in pork luncheon meat (Awuah et al., 2005; Byrne et al., 2006), *Escherichia coli*, and *Listeria*

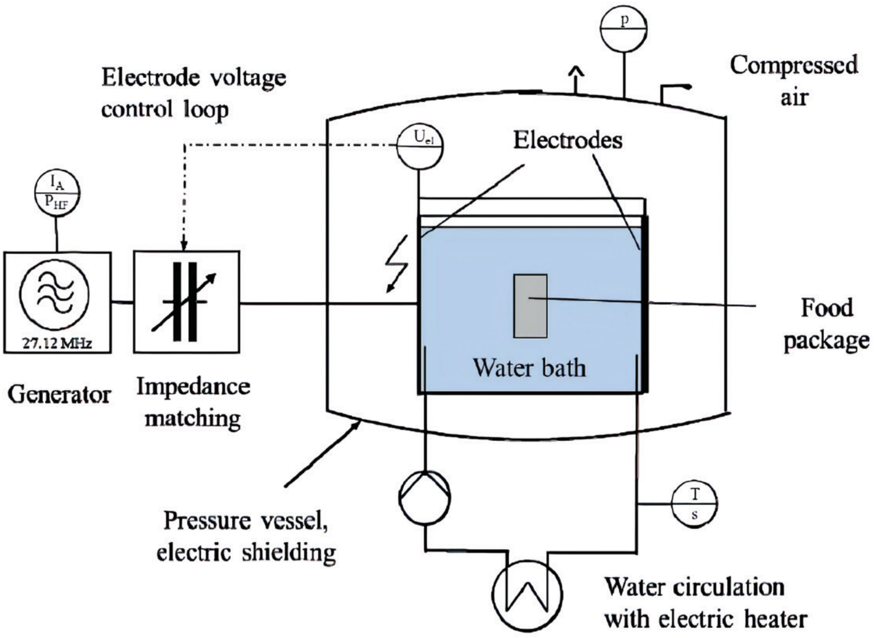

Figure 10. RF with water bath, modified from Felke et al.(2009).

innocua in milk (Awuah et al., 2005), and *Clostridium sporogenes* in scrambled eggs (Luechapattanaporn et al., 2005). In addition, it was reported that using RF-H at 90°C for 5 min displayed thermally destructed *Cronobacter sakazakii* and *Salmonella* spp., the pathogens of most concern, in non-fat dry milk (Michael et al., 2014). Zheng et al. (2017) tested RF-H in order to control anti-fungal efficacy within different types of food. The study was conducted to design a pilot-scale with 27.12 MHz and 6 kW to rapidly pasteurize 3.0 kg corn samples. The result of this study was able to meet the required quality standard used in cereal industry by reducing *Aspergillus parasiticus* in 5–6 log. Moreover, some studies proved that RF plays as an effective heating uniformity. Zhao et al. (2017) indicated that there was no degradation in color of broccoli powder when the RF-H was applied for different time, and the results showed that the total bacteria account was significantly decreased by 4.2 log colony-forming units (CFU)/g with insignificant after RF-H for 5 min. Thus, RF treatment was proven to be a promising technology with a potential to reduce the strength of applied RF and thus contributing to better retention of quality of low-moisture foods.

Future aspects of RF-H

RF technology has considerable potential to replace traditional (water and steam) and microwave heating for food processing. RF offers major advantages including the possibility to immediately penetrate up to 20 cm or more into food for more uniform and efficient heating and limited negative side effects such as reduced food quality or objectionable sensory perception. Food scientists and engineers can anticipate determining optimum RF frequencies, exposure time, and configuration for heating a single food or group of similar foods. At the same time, the relative impact of RF on food quality and sensory perception can be studied with the goal of designing the optimum RF unit for a particular food or group of foods. This heating of foods could be for pasteurization, processing of prepared foods, or consumer reheating, with each situation having different requirements. Since RF units do not have magnetrons, RF units are typically less expensive than microwaves with regard to scaling up from a laboratory to a processing plant application and would thus incur lower maintenance costs.

A potential limitation to optimum RF selection is RF-band designations within the country of operation. For example, current frequencies allocated for industrial, scientific, and medical (ISM) applications typically include those centred at 6.78, 13.56, 27.12, and 40.68 MHz. Any telecommunication devices using these frequencies must be able to withstand RF interference from other devices. Consequently, the use of other frequencies dedicated to telecommunication equipment would require shielding of RF to prevent interference. Fortunately, RF with its longer wavelengths is easier to shield than microwaves.

In the future, consumer microwaves may also be replaced by RF units that are much more efficient at cooking or warming foods. Current microwaves have single button controls for different foods that control the cycling of microwaves over time. However, imagine an RF oven with similar single button controls that can vary the frequency, duration, and cycling of RF in order to maximize the quality and health benefits of a particular food. The research results with RF-H over the past few decades have clearly shown that in the near future, RF-H will be a very attractive processing technology to provide safe and high quality of food products because of its ability to penetrate deeply with rapid uniform heating.

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Conflict of interest statement

None declared.

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