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REVIEW

Radio frequency pasteurization and disinfestation techniques applied on low-moisture foods

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ABSTRACT

The shelf life of foods is usually limited due to the frequent contamination by pests and microorganisms. Although low risk of pathogen contamination and no growth potential compared to those in high water activity animal- or vegetal-derived products, the low-moisture food has still significantly contributed to the total number of foodborne infections and outbreaks. Radio frequency (RF) treatments can be classified as a dielectric heating, which is a promising technology for achieving effective food pasteurization and disinfestations because of the associated rapid and volumetric heating with large penetration depth. The RF technique could be applied at low-moisture food as both the dipole dispersion and ionic conductivity may play effective roles. It can selectively heat and kill the microorganisms/pests without damaging the agricultural product because of the large difference of dielectric loss factors between target microorganisms/pests and host foods. In this article, the low-moisture foods sterilized and disinfested by RF energy are reviewed through basic theories, dielectric properties, heating effect, and uniformity. The potential research directions for further RF heating applications are finally recommended in low-moisture foods.

KEYWORDS

Radio frequency; Pasteurization; Disinfestation; Dielectric properties; Heating uniformity

Low-moisture food is a large category of foodstuffs, including tree nuts, dried species, flour, legumes, grains, and cereals. It is normally considered as a shelf stable product since its low-moisture content usually prevents bacterial growth and multiplication. Low-moisture foods cannot support microbial growth and are commonly considered as "low risk" in terms of further pathogen contamination and no growth potential compared to those in high water activity animal- or vegetal-derived products. The microorganisms can survive for long time and grow quickly as soon as the environment becomes favorable, resulting in increasing numbers of foodborne infections and outbreaks (Beuchat, Mann, and Alali 2013). To ensure the safety of low-moisture foods and extend their shelf life, some necessary pasteurization and disinfestation techniques should be applied on this category of foodstuffs.

Traditional thermal pasteurization and disinfestation methods can hardly be applied on low-moisture content food as the low heat transfer within bulk materials could be observed and the thermal tolerance of pests and microorganisms would increase with reducing water activity (Liu, Tang, et al. 2018). Fortunately, dielectric heating has been successfully proposed for processing low-moisture content foods. Dielectric processing covers both microwave (MW) and radio frequency (RF) heating, which depends on the wavelength of the electromagnetic waves. Typically, the electromagnetic wavelength ranged from 10 to 10^{-3} m can be considered as the dielectric range (Datta and Anantheswaran 2001). MW (300–300000 MHz) and RF waves (0.003–300 MHz) are parts of the electromagnetic spectrum and generate heat in dielectric materials, such as low-moisture foods, through dipole rotation and/or ionic conduction (Ramaswamy and Tang 2008). Usually, MW of 2450 and 915 MHz and RF of 13.56, 27.12, and 40.68 MHz are allocated for industrial heating applications (Alfaifi et al. 2013).

Two mechanisms of creating heat energy under electromagnetic fields are described below:

1. Dipolar polarization plays one of the important roles in heating agricultural products under electromagnetic fields. Many molecules, such as water, can be dipolar polarized in the electromagnetic field. Other molecules may become "induced" dipoles because of the stresses from the electric field. Dipolar polarization is either inherent to polar molecules (orientation polarization), or induced in any molecules in which the asymmetric distortion of the nuclei is possible (distortion polarization). When an external electromagnetic field is applied on dipolar molecules, the distance between charges within each permanent dipole is related to chemical

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Table 1. Literatures on performance of disinfestation/pasteurization in low-moisture food treated by RF energy.

Hazardous material	Target microorganism	Temperature	Source
Disinfestation			
Almond	Indianmeal moth, navel orangeworm & red flour beetle	63 °C	Gao et al. (2010)
Brown Rice	Rice weevil egg	60 °C	Chen et al. (2016)
	Adult rice weevil	50 °C	Zhou and Wang (2016a, 2016b)
Bulk Canola Seed	Rusty grain beetle	30–80 °C	Yu, Shrestha, and Baik (2015)
Coffee bean	Coffee berry borer	48 °C	Pan et al. (2012)
Chickpea and lentil	Cowpea weevil	60 °C	Jiao, Johnson, et al. (2011)
Dry soybean	Indian meal moth	25–50 °C	Huang, Chen, and Wang (2015)
Dried legume	Pulse beetle	56–60 °C	Johnson, Wang, and Tang (2010)
Grain	Rusty grain beetle	15–75 °C	Shrestha and Baik (2013)
In shell walnut	Fifth-instar navel orange worm	52-60 °C	Wang et al. (2007)
Milled rice	Adult rice weevil	25–50 °C	Zhou et al. (2015)
	Immature rice weevil	50 °C	Jiao et al. (2017)
Pistachio	Indianmeal moth	55 °C	Ling et al. (2016)
Rough rice	Adult rice weevil	50 °C	Zhou and Wang (2016a, b)
Rapeseed	Red flour beetle	60 °C	Yu, Shrestha, and Baik (2016)
Rice Flour	*Sitophilus oryzae* and Total numbers of colony	60 and 100 °C	Li, Chen, and Yao (2015)
Raisin	Navel orange worm and Indianmeal moth	23–55 °C	Alfaifi et al. (2016)
Pasteurization			
Bread loaf	*Penicillium citrinum* spore	53–68 °C	Liu et al. (2011)
Beef jerky	*Staphylococcus aureus*	50 and 60 °C	Kim et al. (2014)
Corn grain	*Aspergillus parasiticus*	70 °C	Zheng et al. (2016, 2017)
Peanut butter	*Salmonella*	60–70 °C	Jiao, Tang, and Wang (2014)
In-shell almond	*Salmonella*	73 °C	Gao et al. (2011)
Nostoc sphaeroides	Total numbers of colony	68 °C	Xu, Zhang, et al. (2018)
Red pepper powder	*Salmonella typhimurium*	70 °C	Hu et al. (2018)
Semi-dry dates	*Carpophilus hemipterus*	42 °C.	Pegna et al. (2017)
Wheat flour	*Enterococcus faecium*	75–85 °C	Xu, Liu, et al. (2018)
	Salmonella	60–70 °C	Jiao, Tang, and Wang (2014)
	Enterococcus faecium and *Salmonella*	75–85 °C	Liu, Ozturk, et al. (2018)
	Salmonella and *Enterococcus faecium*	75 °C	Villa-Rojas et al. (2017)
Walnut shell	*Staphylococcus aureus*	26–56 °C	Zhang et al. (2018)

bonding and remains constant in orientation polarization. In another word, the direction of polarization itself rotates, but the electromagnetic field tries to pull them into alignment. However, as the field decaying back to zero (relaxes condition), the dipoles return to their random orientation only to be pulled toward alignment again as the electromagnetic field builds up to the opposite polarity. This causes an energy conversion from electromagnetic field (Mujumdar 2007). It should be noted that the dipolar polarization depends on the molecular weight and electromagnetic frequencies, and smaller molecular weight materials showed less activities under RF frequencies (Tang 2005, 2015).

2. Ionic conduction is the polarization phenomenon caused by relative displacements between positive and negative charged ions. For instance, in NaCl solution, there are sodium, chloride, hydronium, and hydroxyl ions, all of which are moved in the direction opposite to their own polarity by the electric field. As the result, they collide with unionized water molecules when the polarity changes the ions acceleration in the opposite fashion. This phenomenon occurs millions of times depending on the frequency and may cause large numbers of collisions and transfer the friction energy to heat (Robert 2007).

In agricultural products, dipolar polarization and ionic conductivity play the roles for heating during dielectric treatments depending on frequency and food compositions (in particular salt content) (Wang, Tang, et al. 2003). These features make RF energy suitable for processing low-moisture food because ionic components are dominant. Major literature reports show that athermal effects do not exist in dielectric heating systems (27.12 MHz) for microbial inactivation, suggesting that the practical RF pasteurization process should be developed based solely on thermal effects (Kou et al. 2018). However, a comprehensive review on dielectric heating, particularly using RF energy, is lacking for processing low-moisture food based mainly on the heating performance, heating uniformity, computer simulation evaluation, and production quality analyses. In this article, the basic theories, dielectric properties, heating effect, and uniformity were reviewed to evaluate the effect of RF techniques on pasteurizing and disinfesting low-moisture food. Potential applications and recommendations of future research directions using this RF technology were also provided.

Background and heating mechanism

Over the years, dielectric heating techniques have been studied for the pasteurization of foods as diverse as milk and milk products (Zhu, Guo, and Jia 2014), fruit, and vegetable products (Wang et al. 2008; Alfaifi et al. 2013, 2014, 2016), flours (Jiang et al. 2016), spices (Hu et al. 2018; Ozturk et al. 2018), nuts (Li et al. 2017), beef (Kim et al. 2014), and whole meals (Liu et al. 2011). RF treatments have also been used for disinfesting postharvest agricultural products, including seeds, nuts, spices, meats, and corns (Piyasena et al. 2003; Marra, Zhang, and Lyng 2009) (Table 1).

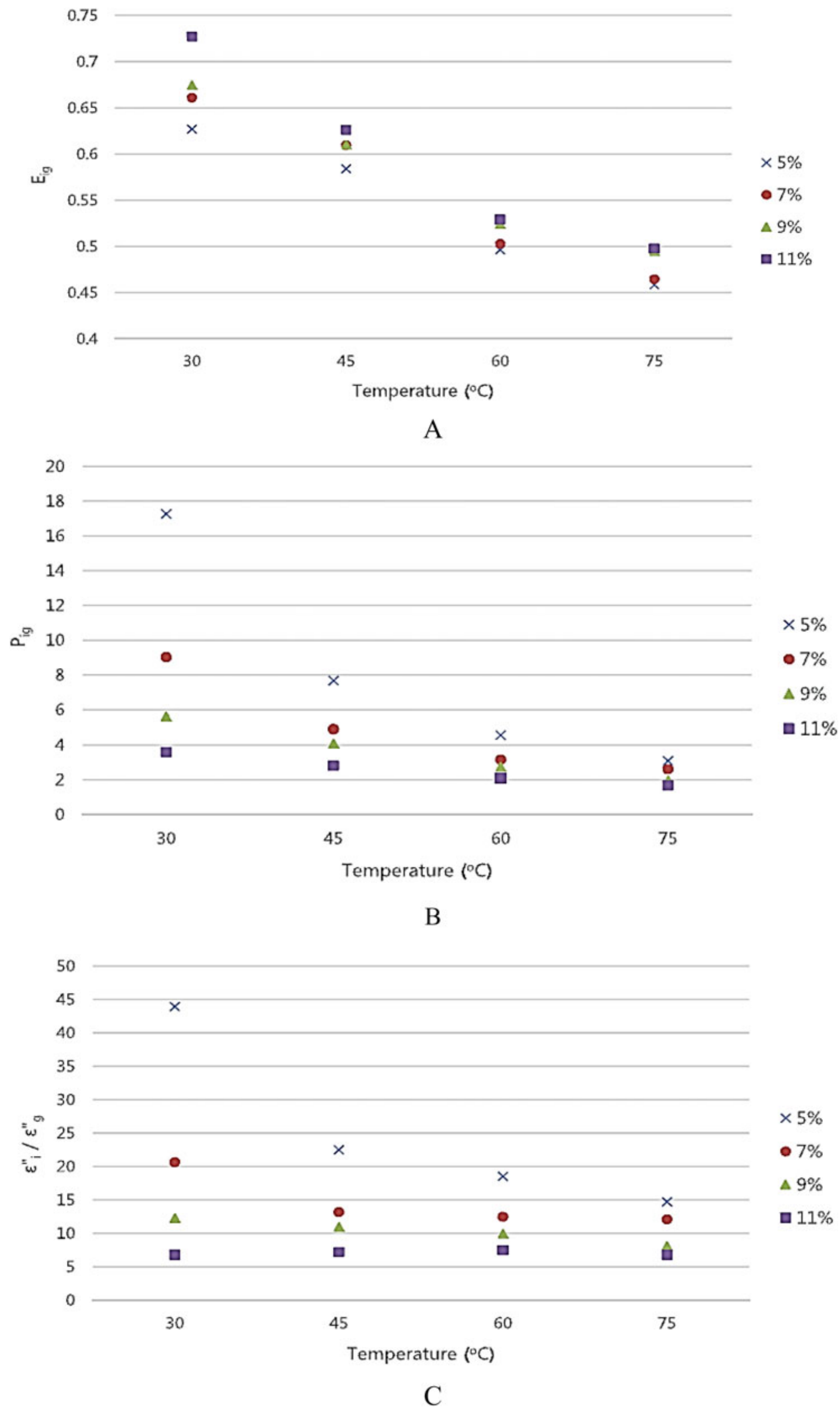

Figure 1. The ratio of approximated electric field strength of rusty grain beetle (*C. ferrugineus* S.) to canola seed (*B. napus* L.) (Yu, Shrestha, and Baik 2015) (A) Rusty grain beetle to canola seed power dissipation factor (B) The ratio of dielectric loss factor for canola seed and rusty grain beetle (C) as a function of moisture content and temperature at 27.12 MHz and four moisture content levels at the wet weight basis.

Traditional pasteurization/disinfestation methods mainly rely on the conventional heat conduction and convection heat transfer in the product required to control the pathogens/pests, while RF heating can raise the temperature of the whole volume food to pasteurization/disinfestation level within a short time period because of fast dielectric heating. However, the results suggest that athermal effects show a limit effect in RF systems at 27.12 MHz with low electrical field intensity for microbial inactivation and the practical RF pasteurization process should be developed based mainly on thermal effects (Wang, Wig, et al. 2003; Kou et al. 2018).

The dielectric properties of materials are of critical importance in understanding the interaction of RF electromagnetic energy with those materials. These properties, along with thermal and other physical properties, and the characteristics of the electromagnetic fields determine the absorption of electromagnetic energy and consequent heating behavior of food materials in dielectric heating applications. The dielectric properties of most materials vary with several factors. In food materials, the amount of water in the material is generally a dominant factor. The dielectric properties also depend on the frequency of the applied alternating electric field, the temperature of the material, and on the density, composition, and structure of the material (Hou, Johnson, and Wang 2016).

Dielectric properties of food materials are usually constituted by the dielectric constant (ε') and the dielectric loss factor (ε''). The ε' describes the ability of a material to store energy when it is subjected to an electric field, influencing the electric field distribution and the phase of waves traveling through the material. The ε'' influences both energy absorption and attenuation and also describes the ability to dissipate energy in response to an applied electric field or various polarization mechanisms, which commonly result in heat generation (Mudgett 2007). The dielectric properties of materials dictate, to a large extent, the heating behavior of the materials when subjected to MW or RF fields. The power dissipated per unit volume P (W/m^3) in the dielectric material can be expressed as (Mudgett 2007):

$$P = \sigma E^2 = 55.63 \times 10^{-12} f \varepsilon'' E^2 \tag{1}$$

where σ is the conductivity (S/m) $\vec{E}$ is the magnitude of electric field intensity (V/m) and f is the frequency (Hz).

Moisture content is the main factor to influence the dielectric properties of foodstuffs. For foods with low-moisture content, dipole dispersion of free water molecules is negligible, so the bound water plays a major role in dielectric heating for the frequency range from 20 to 300 MHz. Bound water is a form of water that has its mobility between ice and free water, its molecules have a lower relaxation frequency than free water at around 100 MHz (20 °C) (Huang et al. 2018), and its magnitude is also much smaller than that of free water. It could be deduced that both the bound water and Maxwell–Wagner's effects contribute to the dielectric properties at a very low range of electromagnetic frequencies comparing with free water and ionic effects. This explains the low values of dielectric properties in low moisture foods.

RF heating can selectively heat and kill microorganisms without damaging the agricultural product because the difference of dielectric loss factors between microorganisms and foods is large (Hou, Johnson, and Wang 2016). The possibility of RF pasteurization/disinfestation has been studied at Washington State University since 2000. The studies have led to experimental data for differential heating based on dielectric properties of various pests and their host agricultural materials over a wide temperature range (Tang et al. 2000; Wang et al. 2001; Wang, Tang, et al. 2003; Monzon et al. 2004; Wang et al. 2008; Gao et al. 2010; Guo et al. 2010; Jiao, Tang, et al. 2011; Alfaifi et al. 2014).

Table 2. Dielectric properties (mean ± SD of two replicates) of NaCl solutions with 10 electric conductivities at 22 °C and 27.12 MHz (Jiao, Tang, et al. 2014).

Electrical conductivity (S/m)	Dielectric properties	
	ε'	ε''
0.03	77.33 ± 0.12	18.12 ± 0.62
0.05	78.21 ± 0.93	30.47 ± 1.32
0.10	78.95 ± 0.57	36.18 ± 3.58
0.15	80.17 ± 0.81	64.93 ± 7.53
0.2	79.29 ± 0.13	119.24 ± 9.31
0.3	80.65 ± 1.03	155.99 ± 10.06
0.5	80.63 ± 0.27	277.99 ± 19.28
1	83.08 ± 0.84	573.45 ± 17.73
2	87.03 ± 0.43	1080.15 ± 23.41
3	91.56 ± 2.59	1577.03 ± 36.52

As analyzed by Yu, Shrestha, and Baik (2015), the electric field strength within the insects was weaker than that within the canola seeds by around 0.46–0.73 times. Nevertheless, the power dissipation in the insects was higher comparing to that within the canola seeds by approximately 1.7–17.3 times. The dielectric loss factor of the insects was higher than that of the canola seeds by around 6.8–43.9 times. The authors pointed out that the rate of temperature increase of insects was affected by power dissipation, bulk densities, and specific heats of the insects. By considering these factors of the canola seed and insect, the calculated temperature increment rate of the insect bodies was 1.4–10.1 times higher than that of canola seeds (Fig. 1). Ozturk et al. (2016) studied the dielectric properties of dried vegetable powders, and the results showed that dielectric properties of vegetable powders were influenced by moisture content, compaction density and temperature of the samples, and the RF frequency. Both the ε' and ε'' increased with increasing moisture content and temperature, but decreased with increasing frequency. Additionally, dielectric properties of samples increased with compaction density to a peak and then decreased. Ozturk et al. (2018) also investigated the dielectric properties of various seasoning spices and their mixtures with RF heating. The effects of the major factors, including moisture content, compaction density, temperature of the samples, and the RF field intensity, directly influence the dielectric heating performance. The experiments about dielectric properties of peanut kernels associated with MW and RF drying were carried out by Zhang et al. (2016). It can be observed that both ε' and ε'' of peanut kernels decreased sharply with increasing frequency over the RF range (10–300 MHz), but gradually over the MW range (300–4500 MHz). Both ε' and ε'' increased with increasing moisture content and temperature. The rate of increasing was greater at higher temperature and moisture levels than at their lower levels. The similar conclusion has also been obtained from Alfaifi et al. (2013) and Yu, Shrestha, and Baik (2015), revealing that dielectric properties were essential for understanding the interaction between electromagnetic fields and foods. The data from Jiao, Tang, et al. (2014) showed that except for initial moisture content and

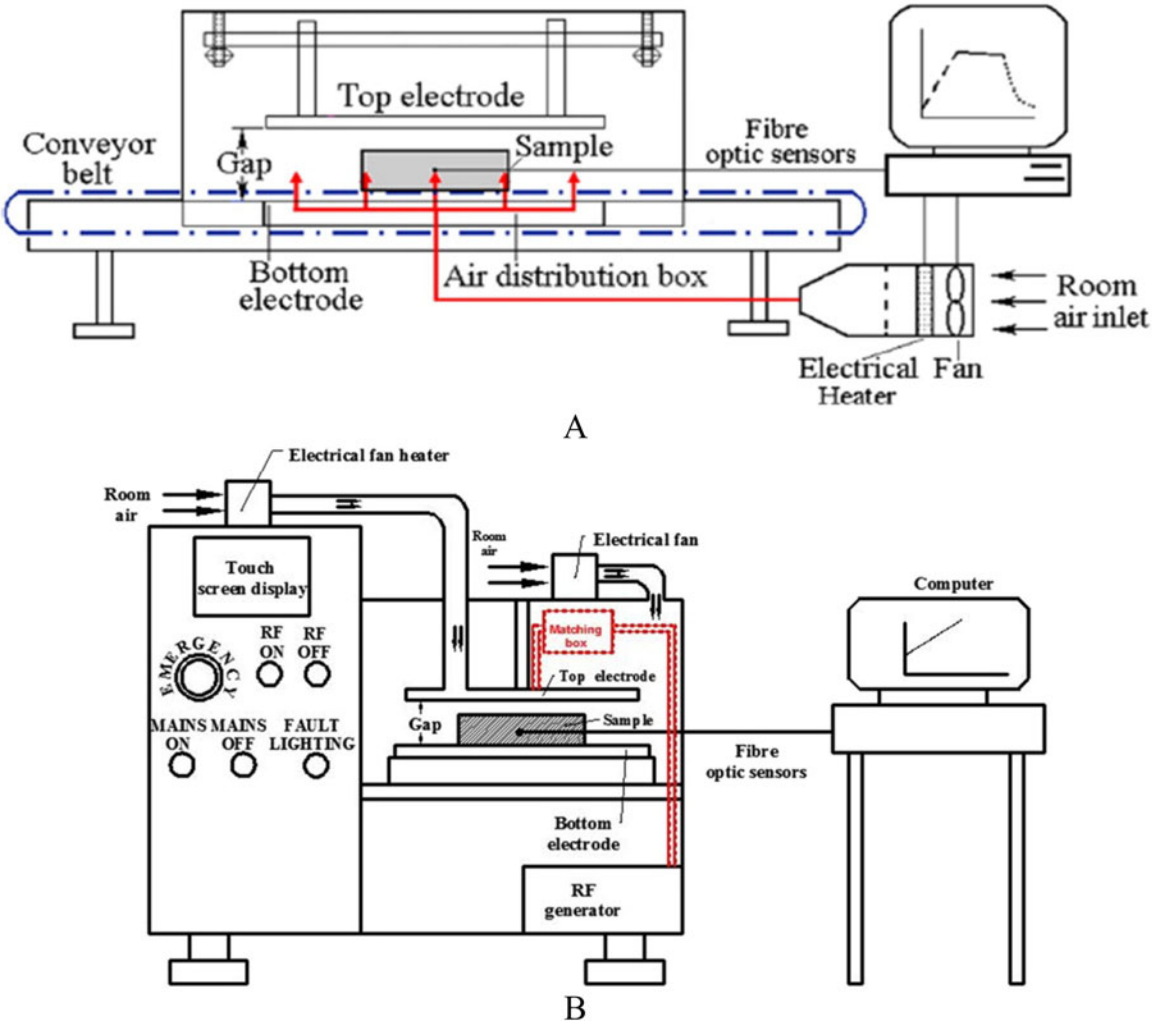

Figure 2. Schematic view of (A) the free running oscillator RF system showing the plate electrodes, conveyor belt, and the hot air system, and (B) 50 Ω RF system showing the plate electrodes, control panel and the hot air system (Zhou, Guo, and Wang 2017).

temperature, salt concentration would also alter the electric conductivity of food products, thereby change the dielectric properties and the heating rate (Table 2).

The available RF systems for converting electric energy to thermal one can be divided into two distinct groups: the widely applied conventional RF heating equipment (free running oscillator RF system) and the power-regulated 50-Ω RF heating equipment (Marchand and Meunier 1990). Whether conventional or 50-Ω dielectric heating systems are used, the RF applicators mostly fall into one of three main types: the through field applicator, the fringe field applicator, and the staggered through field applicator (Robert 2007). Conceptually, a thorough field RF applicator (with a pair of parallel plates) is the simplest and the most common design of RF applicators in which the lossy material is placed between the two electrodes to form a parallel plate capacitor. This type of applicator is mainly used for heating bulk materials or relatively large and thick objects. The 50-Ω RF system is a relatively new technology to provide a fixed frequency compared to the conventional RF system and to precisely control power and feedback (Jones and Rowley 1996). Unfortunately, the 50 Ω RF systems are more expensive than the conventional ones and have not been popularly used by food industries until now (Fig. 2).

Heating performances

The most evident characteristic of dielectric heating is the high heating rate. The frequency of RF systems is usually smaller than that of MW systems, resulting in a slow spinning rate of polar molecules in foods. Such the phenomenon brings RF treatments to create less dipolar frictional times compared with MW systems. However, RF heating still shows some superiority compared with traditional and MW heating (Jiang, Liu, Wang et al. 2018). The deeper penetrability of electromagnetic wave under lower RF frequencies also ensures that the core temperature of large samples can be raised faster than MW heating. Electrode gap distances with thermal and dielectric properties of the materials are the direct elements to determine the heating rate in RF treatments. Zhou et al. (2015) studied the heating rate of milled rice when subjected to the 27.12 MHz pilot-scale free running oscillator RF system and found that the milled rice temperatures increased almost linearly with the heating time under the given three electrode gaps. The heating rates

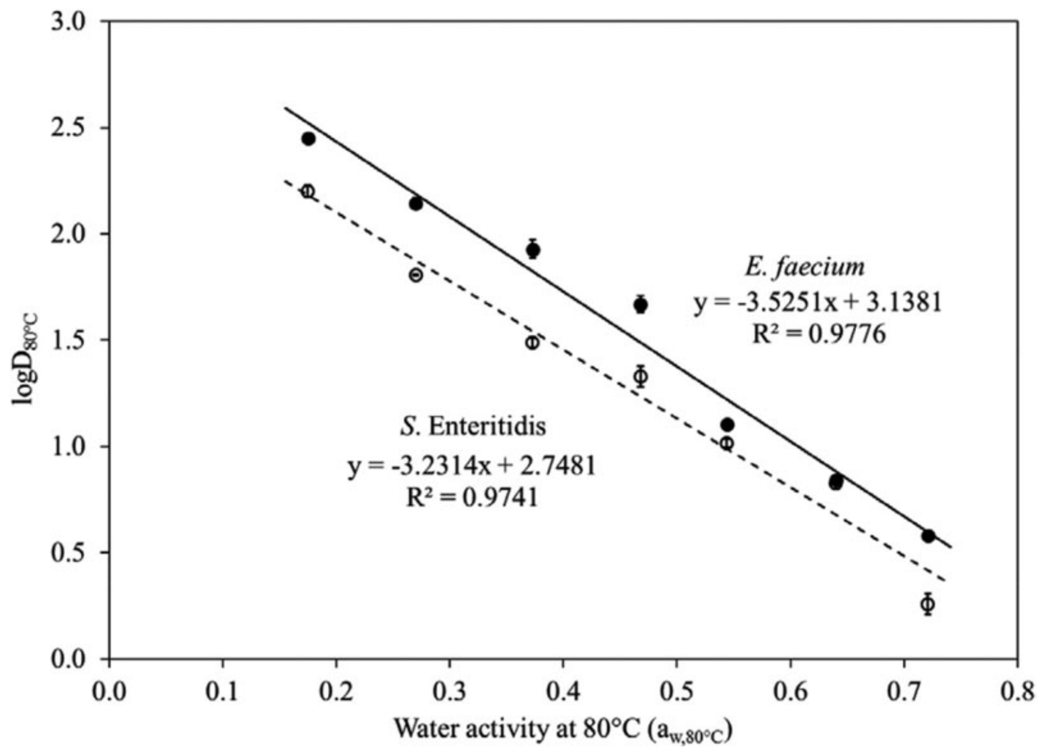

Figure 3. Log$D_{80°C}$ (decimal reduction time to achieve 90% population reduction at 80 °C) values for *S. Enteritidis* and *E. faecium* in SiO_2 increased with decreasing water activity levels at 80 °C ($R^2 = 0.98$) (Liu et al. 2018).

decreased with increasing electrode gaps, about 2.7, 4.3, and 7.0 min were needed to heat the 3.9 kg milled rice samples from 25 to 50 °C and the heating rates were 9.25, 5.80, and 3.56 °C/min for electrode gaps of 10, 11, and 12 cm, respectively. It took only 4.3 min for the center temperature of RF heated milled rice to reach 50 °C, as compared to 480 min for hot air heating to reach 48 °C.

As described in Equation (1), the heat energy generation in food when placed in an electric field is determined by the applied frequency, the electric field strength in food, and the dielectric loss factor of the sample (ε''). When the electric field strength and the frequency are constant, foods with higher dielectric loss factors may convert more electromagnetic energy to heat than food with lower dielectric loss factors, which correspond to faster heat generation during the RF heating. To be one of the most important factors changing the ε'', water content with the appropriate ionic strength is an important component of foods and considered as one of the key factors to influence microbial thermal resistance. The corresponding water activity (a_w) is generally used to represent the interaction of cells with water, because it can reflect the intensity to the associated water with nonaqueous components at a microscopic level. Therefore, initial a_w of samples could have direct relationship with the thermal resistance of pathogens and is often used to simulate the inactivation of pathogens (Santillana Farakos, Frank, and Schaffner 2013). For example, the thermal resistance of *Salmonella* increased with reduced water activity in wheat flour, almond flour, and whey protein, representing carbohydrate-, fat-, and protein-rich food systems (Xu et al. 2019). They found a linear relationship between logarithmic *D*-values of *Salmonella enteritidis PT30* and a_w (at treatment temperatures) with fair goodness of fit ($R^2 = 0.89$) across food matrices. The similar trends were also obtained by Liu, Tang, et al. (2018) that reductions in the a_w values at 80 °C of bacterial cells exponentially increased in the *D*-80 °C values for *S. enteritidis* and *Enterococcus faecium* on silicon dioxide as the carrier (Fig. 3).

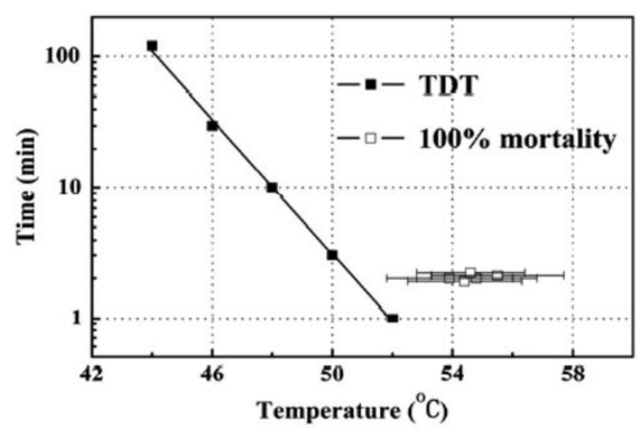

Figure 4. Final pistachio kernel temperatures (mean ± SD) after RF treatments related to insect mortality as determined by thermal-death-time (TDT) curve for complete kill of fifth instar Indianmeal moth larvae obtained in a heating block system (Ling et al. 2016).

Inactivation kinetic of pests and microorganisms

One of the most important advantages of RF heating is the selective heating of the insect pests and microorganisms, in which the pests/microorganisms in foods would be destroyed at the temperatures lethal to them but with a minimal or tolerable thermal degradation to the food qualities.

Table 3. Effect of RF treatment (50 °C, 5 min) on nutritive qualities of rough, brown, and milled rice (Jiao et al. 2017).

Nutritive quality	Rough rice		Brown rice		Milled rice	
	Control	RF	Control	RF	Control	RF
Protein content (%)	7.09 ± 0.09a	6.98 ± 0.07a	8.98 ± 0.55a	8.88 ± 0.28a	9.06 ± 0.05a	8.86 ± 0.12a
Fat content (%)	1.83 ± 0.02a	1.72 ± 0.03a	1.81 ± 0.02a	1.79 ± 0.08a	1.53 ± 0.03a	1.48 ± 0.06a
Amylose content (%)	8.99 ± 0.01a	8.33 ± 0.52b	11.29 ± 0.01a	10.40 ± 0.21b	17.28 ± 0.01a	16.36 ± 0.23b
Fatty acid value (mg/100 g)	14.96 ± 0.85a	14.41 ± 0.73a	15.52 ± 0.78a	14.69 ± 0.99a	3.54 ± 0.19a	3.49 ± 0.18a

Although the frequency is the same, the ε' and ε'' for the insects/microorganisms and food are different as these dielectric properties depend on various material properties, such as concentration of ion, moisture content, and density. If the ion concentration and moisture content of the pests/microorganisms are higher than those of the food, RF heating can be very effective for controlling them with high temperatures.

The inactivation kinetic studies of pest and microorganism in lower moisture food have also been carried out by various researchers, including *Sitophilus oryzae* in rice (Zhou and Wang 2016b), coffee berry borer in coffee bean (Pan et al. 2012), Indianmeal moth in Pistachio (Ling et al. 2016), *Salmonella* in wheat flour, almond flour, and whey protein (Xu et al. 2019), *Salmonella* and *Enterococcus* in wheat flour (Villa-Rojas et al. 2017) and in silicon dioxide (Liu, Tang, et al. 2018), fungi in wheat and corn seeds (Jiao, Zhong, and Deng 2016; Zheng, Zhang, and Wang 2017), and enzymes in wheat germ (Ling, Ouyang, and Wang 2019). It should be figured out that once the temperature reaches the thermal death time (TDT), microorganisms would be inactivated within a short period. The data from Ling et al. (2016) revealed that only 5.6 and 5.5 min were needed to raise the center temperature of 1.8 kg in-shell and 2.0 kg shelled pistachios to reach 55 °C using RF energy, which ensured 100% mortality of fifth-instar Indianmeal moth in the infested pistachios. The results also agreed with those reported by Johnson, Wang, and Tang (2003) (Fig. 4). RF treatments also showed high efficiency on inactivating the microorganism of extremely resistant to lethal conditions in low-moisture foods. Hu et al. (2018) investigated the inactivation kinetics for *Salmonella typhimurium* in red pepper powders treated by RF energy. The survivors of *S. typhimuriumin* in the red pepper powders with a_w of 0.57 were reduced by 3.2, 3.9, and 5.6 log CFU/g after RF heated to 70 °C, 80 °C, and 90 °C with holding for 180 s, respectively. However, under the same RF treatment conditions, log survivors of *S. typhimurium* in the red pepper powders with a_w of 0.64 could be reduced by 4.8, 5.2, and 6.1 log CFU/g, respectively. When the initial a_w increased to 0.71, RF heating to 50–70 °C with a holding time of 180 s resulted in comparable log reductions. Further increase of initial a_w of the powders to 0.74 led to more log reductions of *S. typhimurium* compared with that of initial a_w of 0.71 under the same RF treatment conditions. The results proved that the initial a_w of the powders not only affected the RF heating profile, but also influenced the pasteurization efficiency of high resistant pathogens to lethal treatments. These conclusions are also supported by Xu et al. (2019) and Liu, Tang, et al. (2018).

The large-scale continuous RF treatments with a 27.12 MHz, 6 kW power to control rice weevil were carried out by Zhou and Wang (2016a) in milled, brown, and rough rice. At the conditions (electrode gap: 11.5 cm, heating rate: 6–8 °C/min, forced hot air surface heating: 50 °C, velocity of sample movements on the conveyor: 12.5 m/h and time: 6 min), the final industrial RF treatment achieved a complete mortality of adult rice weevil and provided acceptable rice quality attributes in moisture content, water activity, color, protein, free fatty acid, and ash. The average heating efficiency and throughput of the RF treatments were 77.7, 76.3, and 74.3%, and 268.8, 247.3, and 224.8 kg/h for milled, brown, and rough rice, respectively.

Impact on the food quality

RF heating is mainly caused by ionic conduction in dielectric materials. It is susceptible whether the other chemical changes happened except for heat effect. However, it cannot be ignored that the features alternation of RF treated food during processing or storage. Jiao et al. (2017) studied the disinfestation of milled rice by RF treatments. The results indicated that no significant ($P > 0.05$) decreases were observed in protein, fat, and fatty acid contents of rough, brown, and milled rice after RF treatment, but amylose content slightly decreased after RF treatment (Table 3). Jiang et al. (2016) figured out electromagnetic wave irradiation would promote the de-chain reaction of starch during dielectric heating. Wang, Zhang, Johnson, et al. (2014) found the mean peroxide value and free fatty acid values increased with the increasing treating time for RF treated nuts, which probably caused by nut oil oxidation at long exposure time and high temperatures.

The qualities of RF-treated rapeseeds were measured by Yu, Shrestha, and Baik (2016). The results indicated that the germination rate of the RF-treated rapeseeds decreased with increasing initial seed moisture content and RF heating temperature. RF treating would cause a loss of mass and roundness of rapeseeds, reducing the market value of seeds. However, the color and quality of oil (peroxide value, *p*-anisidine value, overall oxidative stability, and iodine value) from RF-treated rapeseed were not affected significantly by the RF heating at various moisture contents (5, 7, 9, and 11%) and temperatures (from 30 to 80 °C).

RF heating was used for semi dried date palm (initial moisture content: 18 ± 1.5%) to control *Carpophilus hemipterus* (Pegna et al. 2017). The color data showed that no significant differences of trichromatic coordinate b^* (yellow-blue) between the control and the RF-treated samples were observed. The color variation between treated and untreated

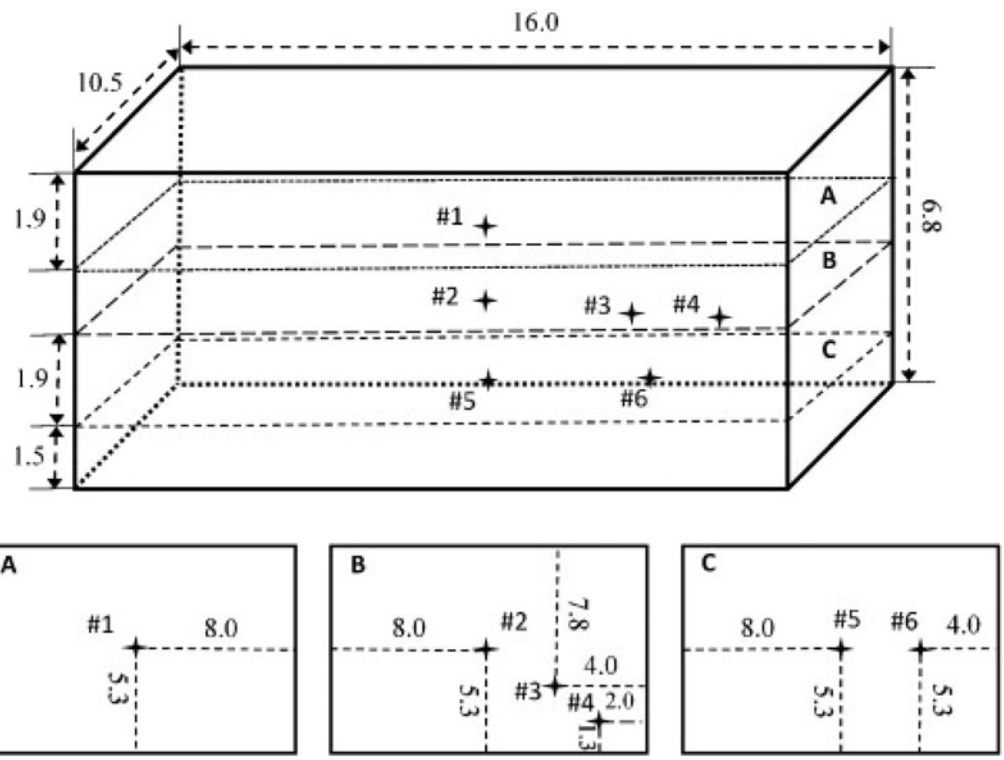

Figure 5. The dimension of the sample and the position of six typical points on three different layers (A, B and C) inside the sample (Jiao, Deng, et al. 2015).

samples expressed by the $\triangle E^*$ value was low and no significant differences were observed.

It also showed no significant differences of pistachio in color data after RF treatment, but the L^* values in inner kernels significantly decreases and a^* values in both inner and ground kernels increase ($P < 0.05$) with storage time, which are caused by chlorophyll and lutein degradations with higher temperatures. The water activity, a_w and fatty acid compositions had no significant change ($P > 0.05$) between control (no RF treating) and RF-treated samples during whole storage periods. The data also illustrated that the mean peroxide values and free fatty acid values increased only after 3 month storage time for RF-treated pistachios, which indicated the inactivation of lipoxygenase enzyme happening after RF heating (Ling et al. 2016).

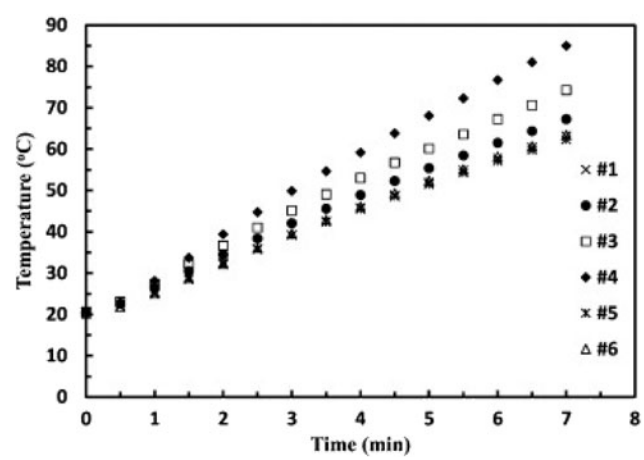

Figure 6. Experimental temperature profiles for six typical points inside the wheat kernels in plastic container after 7.0 min RF heating (electrode gap was 10.0 cm; sample size: $16.0 \times 10.5 \times 6.8\,\text{cm}^3$; sample was placed in the middle of two electrodes) (Jiao, Deng, et al. 2015).

Simulation of RF heating applied on low-moisture content food

A sinusoidal voltage V at a frequency $\omega = 2\pi f$ applied to a pair of parallel plates may create an electric field in the space between the plates. Placing a dielectric material, such as food, between the plates would change the distribution and intensity of the electric field both inside the material and in the air gap on either side of the material. Materials, such as food, in which electromagnetic power is dissipated, are generally referred to as "lossy materials" since some of the electromagnetic energy is "lost" when it is converted into thermal energy inside the material (Datta and Anantheswaran 2001). However, real MW and RF applicators used for food applications are generally more complex devices than the parallel plate applicator. A more complete description of the fields is needed to understand the heating behavior. This is provided by Maxwell's field equations, which describe how a time-varying electric field is accompanied by a corresponding time-varying magnetic field, and vice versa (Peng and Hwang 2015). When coupled with the appropriate boundary and initial conditions, penetration, reflection, transmission, and absorption of the electromagnetic fields completely define the heating performances of a MW and RF applicator (Mingos and Baghurst 1991).

Until the late 1980s, there was little research on the numerical modeling of dielectric heating. This was partially due to the lack of availability of computers with insufficient power to solve the necessary equations (Lorenson and Gallerneault 1991; Huang et al. 2018). Due to advances in

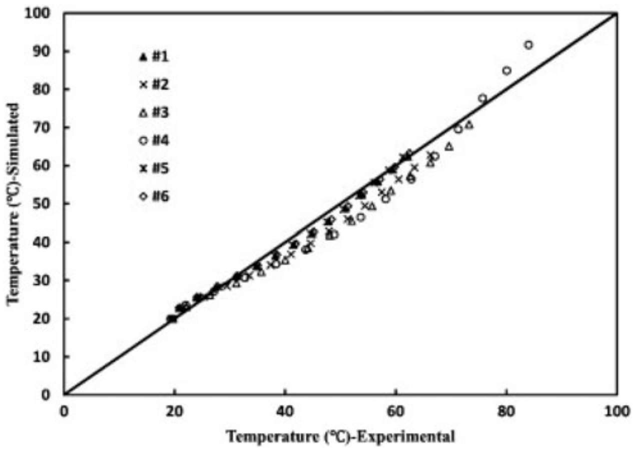

Figure 7. Validation of computer simulation model by comparing experimental data with simulated temperatures after 7.0 min of RF heating (sample size: $16.0 \times 10.5 \times 6.8\,\text{cm}^3$, sample was placed in the middle of two electrodes) (Jiao, Deng, et al. 2015).

computer technology and significant progress in the simulation techniques, the simulation methods were reaching a level of maturity where they can now be considered for use as part of the design process. The finite element method (FEM) and finite difference time domain method (FDTD) are the two most popular methods for simulating MW/RF heating (Datta and Anantheswaran 2001). The others including transmission line matrix (TLM) (Taflove 1988) and method of moments (MoM) (Desai et al. 1992) were rarely used.

Compared with the FDTD, FEM has higher accuracy to model the actual mechanical process. The FEM decomposes the complex geometry to be modeled into a union of elements, each of which has a simple geometry, typically quadrilaterals or triangles in two dimensions and tetrahedra or hexahedra in three dimensions. Since the method does not require a regular grid, it allows a very flexible decomposition of the region (Datta and Anantheswaran 2001).

Jiao, Deng, et al. (2015) used the FEM to calculate the RF heating uniformity of wheat kernels. The computer simulation model for RF heating was built by using COMSOL software (Comsol V. 4.3b, Comsol AB, Stockholm, Sweden). Five different types of meshes including normal, fine, finer, extra fine, and extremely fine were selected to run the simulation. The accuracy of the results was affected by the meshing size; generally the small element size would result in more accurate results, but it would take much longer time to calculate. To validate the computer model, simulated temperature profiles were compared with the experimental real-time temperature results, using the plastic container filled with 910 g of wheat kernels heated by RF energy with six typical positions (Fig. 5). Compared with the data from simulated and experimental temperatures (Fig. 6), all the data points were distributed around $y = x$ line (Fig. 7), indicating good agreement between the simulated and experimental temperatures. Similar simulation was also carried out by Alfaifi et al. (2014) for raisins, Huang, Zhang, et al. (2016) for dried soybeans, Chen et al. (2017) for wheat, and Zhang, Huang, and Wang (2017) for peanut.

Ozturk et al. (2016) determined if the moisture content or temperature had a significant effect on ε', ε'', and penetration depth of broccoli powder. The results indicated that each regression model provided a good fit to the experimental data at the significance level $p < 0.0001$ with a high coefficient of determination ($0.968 < R^2 < 0.998$). The linear relationships between heating rate and moisture content and dielectric loss factor of broccoli powder were also developed. Those regression models can be used to predict the ε' and ε'' of broccoli powder with moisture content between 6.9% and 14.9%, temperature between 20 °C and 80 °C, and heating frequencies of 13.56 and 27.12 MHz.

RF heating uniformity in low-moisture content food

For the application of RF treatment, heating uniformity has always been the first concern. Although the relatively longer wavelength of RF energy (comparing to MW) usually results in more predictable temperature distributions in foods, some over-heating is still a problem for foods heated in containers. Sample size, shape, surface area, poor RF heater design, and nonhomogeneous dielectric properties of materials could result in nonuniform electric field distribution, in turn causing nonuniform temperature distribution (Alfaifi et al. 2014). Nonuniformity temperature distribution would happen if corner/edge effect, thermal runaway, and focusing heating occurred (Mudgett 1988). Alfaifi et al. (2016) considered that the heating uniformity was improved by rounding the corners of the containers and reducing sharp edges on the packages, modifying electrode configurations, and applying forced air after RF heating. It was also reported that when wheat kernels were placed inside polypropylene (PP) plastic cuboid container heated by 50-Ω RF system, hot spots were located at the corner of samples in cuboid shape, and cold spots depended on the sample vertical position in the RF cavity. It was also found that cold spots were at the center of the top and bottom layers when the sample was placed at the middle position between the two parallel electrodes. A larger sample size had better RF heating uniformity, especially when sample size equaled to the size of the top electrode, indicating that RF energy is more suitable for treating large-size materials (Jiao, Deng, et al. 2015). For the low-moisture content food materials, therefore, sample in large size, and placed in the middle or slightly lower than middle position between the two parallel electrodes achieved better temperature uniformity.

Heating uniformity improvement is the research hotspot of RF-related technologies. Except for re-designing the RF generating system, other methods including package, homogeneity, multilayer heating, exogenous high dielectric adding, geometry changing, sample movement, and auxiliary heating could be used to improve the heating uniformity. Huang, Marra, and Wang (2016) figured out that the RF heating uniformity in food samples were clearly influenced by dielectric properties and density of the surrounding container. The optimum RF heating uniformity in food products could be achieved with a smaller density value of the surrounding container. The correlations of dielectric

Table 4. Enzyme activity (POD, SOD, and CAT) of wheat and corn seeds before and after different hot air-assisted RF treatments (Jiao, Zhong, and Deng 2016).

	Control			60 °C, 10 min			65 °C, 10 min			70 °C, 10 min		
	POD (U g^{-1})	SOD (kU g^{-1})	CAT (U g^{-1})	POD (U g^{-1})	SOD (kU g^{-1})	CAT (U g^{-1})	POD (U g^{-1})	SOD (kU g^{-1})	CAT (U g^{-1})	POD (U g^{-1})	SOD (kU g^{-1})	CAT (U g^{-1})
Wheat Seed	268.7 ± 42.2	8.02 ± 0.44	8.9 ± 0.8	325.1 ± 28.0	14.10 ± 1.86	11.0 ± 1.4	386.1 ± 10.4	12.47 ± 1.78	7.9 ± 1.4	209.7 ± 2.43	6.85 ± 0.91	5.0 ± 0.8
Corn Seed	52.8 ± 15.4	11.23 ± 1.77	11.0 ± 3.6	73.2 ± 6.5	27.16 ± 3.77	11.4 ± 2.1	60.6 ± 8.9	15.76 ± 2.18	13.2 ± 1.3	39.1 ± 3.2	7.38 ± 0.70	7.8 ± 0.8

POD: Peroxidase, SOD: Superoxide dismutase, CAT: Catalase.

properties and density between surrounding container and food products could provide valuable information and strategy to improve the RF heating uniformity in low-moisture foods. Huang, Zhang, et al. (2016) also used two kinds of containers (polypropylene and polystyrene) with dried soybeans and found that the temperature uniformity was greatly improved by placing soybean samples in the polystyrene container other than the polypropylene one because the dielectric properties of polystyrene were closer to those of the dried soybeans. A mica plate was placed on top of the peanut samples with polypropylene blocks placed in between the samples and also used as a new strategy to improve the RF heating uniformity. The results showed that adding mica plates with the similar dimension to the cold spot of samples and increasing the plate thickness effectively improved the RF heating uniformity. Adding polypropylene blocks also raised sample average temperatures and finally optimized the RF heating uniformity (Zhang, Huang, and Wang 2017). Zheng et al. (2016) found that the corn samples at 15.0% (wet basis, w.b.) in the polyetherimide container had a better RF heating uniformity compared to samples in the polystyrene and polypropylene containers. Polyurethane foams (Wang, Zhang, Gao, et al. 2014) and polyetherimide blocks (Jiao, Shi, et al. 2015) were also used to improve the RF heating uniformity.

Hot air surface heating is also used to enhance the RF heating as it can adjust the heating rate and maintain the sample temperature during holding when the RF power is turned off (Hu et al. 2018). The quality change of wheat and corn seeds heated by hot air-assisted RF energy was carried out by Jiao, Zhong, and Deng (2016). It can be found from Table 4 that hot air-assisted RF treatments at 60 °C or 65 °C with 10 min holding increased the tested enzyme activities for both wheat and corn seeds. When the treatment temperature increased to 70 °C and with 10 min holding, all the enzyme activities decreased significantly ($P < 0.05$) for both seeds compared with control, because high temperature would inactivate enzyme activity. As the physiologic function of seeds, mild hot air-assisted RF treatment temperatures (less than 65 °C) can increase in enzyme activities, thus maybe it would improve the seed vigor. However, total color difference ($\triangle E^*$) results showed no significant difference between each hot air-assisted RF treatment and control for both wheat and corn seeds, indicating that hot air-assisted RF treatments within a temperature range of 60–70 °C for 10 min had no significant ($P > 0.05$) influence on the color of wheat and corn seeds.

Trends and conclusion

In the food industry, RF heating is commonly used in the drying of freshly baked products, wood, and textiles (Jiao et al. 2018). Such RF industrial applications can shorten processing time, reduce working space, and improve product quality compared to conventional heating methods. For foods with low-moisture content, dipole dispersion of free water molecules is negligible and ionic conductivity plays a major role at lower frequencies (27 MHz, for example), while both ionic conductivity and dipole rotation of free water play a combination role at microwave frequencies (e.g. 915 and 2450 MHz) (Wang, Wig, et al. 2003). The superiorities of RF pasteurization and disinfestation over traditional methods can be summarized as follows:

1. Economic and efficient effects: in analyzing the economics of a RF heating system, the costs can be divided into equipment and operating costs, and this latter may be further broken down to tube replacement, general maintenance, electric energy, and working space costs. However, except for the high heating rates, there is an approximately more than 60% overall conversion efficiency of electricity to thermal energy for dielectric heating systems, which is far higher than that of traditional heating systems (Mujumdar 2007). This characteristic ensures RF heating with less cost in energy and operation.
2. Better penetrability and heating uniformity: RF energy can heat products volumetrically in polymeric trays with a large depth of samples due to 11 m of wavelength at 27 MHz.
3. Easy to combination: Typically, hybrid heating methods include processes that employ more than one heater or multiple modes of heat transfer and those that use two or more stages of processing to achieve the desired product quality, energy consumption, processing time, and throughput. A more common definition of hybrid heating would be the successful integration or intelligent combination of two or more conventional pasteurization/disinfestation methods. This method can allow for the emergence of a wide range of new hybrid technologies. For instance, RF heating may combine with hot air, hot water, or vacuum.

As more successful RF treatments are developed in dry products than fresh fruits because of the insensitive to quality changes with higher temperatures compared with fresh fruits and vegetables, the high potential of RF pasteurization and disinfestation could be realized on low-moisture food in industrial processes. However, there is still a need for further studies to bridge the gap between laboratory research and commercial applications. Suggestions are recommended below for future research:

1. Mathematical modeling improves the understanding of RF heating in food and it is essential to continually promote this technology. The computer simulation is needed to expand the scope of RF treatment applications. Further studies should focus on improving the model prediction precision, predicting the microbial population distribution, and improving the RF heating uniformity in industrial systems.
2. Not all agricultural products, especially heat-sensitive food, can tolerate the thermal conditions required to control insect pests and microorganisms. Studies on heat-sensitive and functional components are necessary to evaluate the effects of RF pasteurization and disinfestation on product quality in a given shelf life.
3. Most low-moisture content products are not only infested by pests or microorganisms but pest eggs or microbial spores after harvesting. The study on the lethal kinetics of various possibly contaminated microorganisms is important to develop effective RF pasteurization and disinfestation protocol. It is practical to integrate these disinfestation, pasteurization, and drying purposes together so as to develop a feasible and comprehensive postharvest RF technology.
4. To evaluate the actual capital costs for initial installations and to estimate the energy costs involved in particular treatments, the energy efficiency and operational costs of RF processing further need to be determined. It is useful to improve and optimize design parameters and mathematical modeling for RF heating systems so that laboratory and pilot-scale RF test systems can be transferred to large-scale industry implementation.
5. Although athermal effects of RF treatments could be ignored in common setting, extreme low frequency and high electrical field intensity would be a new research direction to explore the nonthermal effects, which could enhance the microbial inactivation rate and maintain the product quality.
6. There is a lack of data of RF dielectric properties of various foods as functions of frequency, temperature, water content, density, viscosity, and composition. This information is essential for improving understanding of temperature distributions but also is important in the design of RF heating systems.

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