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Radio-Frequency Applications for Food Processing and Safety

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Abstract

Radio-frequency (RF) heating, as a thermal-processing technology, has been extending its applications in the food industry. Although RF has shown some unique advantages over conventional methods in industrial drying and frozen food thawing, more research is needed to make it applicable for food safety applications because of its complex heating mechanism. This review provides comprehensive information regarding RF-heating history, mechanism, fundamentals, and applications that have already been fully developed or are still under research. The application of mathematical modeling as a useful tool in RF food processing is also reviewed in detail. At the end of the review, we summarize the active research groups in the RF food thermal-processing field, and address the current problems that still need to be overcome.

INTRODUCTION

Processing and preservation techniques are used in the food industry to produce safe and high-quality foods and ingredients with extended shelf lives. Most of those techniques rely on thermal energy to inactivate bacteria, insects, and enzymes. These technologies are commonly referred to as thermal-processing techniques. Traditional thermal-processing techniques in the food industry use high-temperature steam, water, or air as the heat source transmitted to the food products. Solid or semisolid foods generally have low thermal diffusivity (Kostaropoulos & Saravacos 1997), which hinders the heat transfer to the center of the foods. The lengthy exposures to high heat-source temperatures normally resulted in food quality degradation at the contact surface between the heat source and the food material. Thus, to make sure the coldest spot in the food matrix receives adequate heat for food safety, food companies have to compromise food quality. To address the increasing demands of consumers for high-quality products, further development of novel food thermal-processing technologies is needed to ensure food safety while improving food quality.

Radio-frequency (RF) heating is a volumetric heating method, which provides fast and deeper heat generation within food matrices. It typically involves electromagnetic waves of 1–100 MHz that penetrate foods and interact with the ions, atoms, and molecules to generate internal heat. RF heating has been applied commercially in the wood, textile, and paper industries, and also to a limited extent in the food industry. However, more applications can be explored for the food industry. The purpose of this review is to introduce the RF-heating mechanism, equipment, and applications in the food industry. It also summarizes current research activities that explore new applications of RF for food safety and discusses limiting factors and challenges.

RADIO-FREQUENCY FUNDAMENTALS

History of Radio-Frequency Heating

RF heating was first used in 1895 as a medical treatment method. In food processing, it was first explored for blanching and then for cooking and dehydrating (Proctor & Goldblith 1948, Moyer & Stotz 1947). In the 1960s, many attempts were made to use RF to thaw frozen foods. In those studies, different frozen food materials were tested using lab-scale and even industrial-scale (25 kW) RF systems. The studied food items included eggs, fruits, vegetables, and many species of fish and meat (with and without bones). These research activities led to successful commercial applications of RF in thawing of fish blocks. Between the 1960s and 1980s, little research was reported from university laboratories on RF heating of foods. Equipment companies were the drivers behind the expansion of RF heating to other food applications, including finish drying of bakery products (Holland 1963, Mermelstein 1998, Rice 1993). Since the 1990s, with increasing computational power and commercially available dielectric property and temperature measurement devices, new research findings were reported from several university laboratories on RF heating for postharvest disinfestation of agriculture produce (Mitcham et al. 2004; Monzon et al. 2004; Wang et al. 2002, 2003a) and sterilization and pasteurization of foods (Luechapattanaporn et al. 2004, 2005; Wang et al. 2003c). Most of these researchers stated the necessity for more research to improve heating uniformity. In spite of numerous academic research projects, the progress toward the commercialization of applications for RF disinfestation/sterilization/pasteurization technologies remains very slow for various reasons, including a lack of knowledge within the equipment manufacturers that holds back the evolution of equipment, the lack of research funding needed to support systematic research and scale-up, and the lack of general awareness of the potential advantages of RF heating in the food industry.

Radio-Frequency Heating Mechanism

Dielectric properties are the intrinsic properties of materials describing the degree of a material's interaction with an alternative electrical field, and quantifying its ability for reflecting, storing, and transmitting electromagnetic energy. The dielectric properties can be expressed as

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

where ε^* is the complex relative (to vacuum) permittivity; ε' is the relative dielectric constant, which is a measure of the ability of a material to store electromagnetic energy; j is the imaginary unit; and ε'' is the relative dielectric loss factor, which is a measure of the ability of a material to dissipate electromagnetic energy into heat. Many factors affect the dielectric properties of a material, such as frequency, temperature, and food composition and density.

Penetration depth (d_p, m) is defined as the distance from the surface of a dielectric material when the incident power is reduced to *1/e* ($e = 2.718$) of the power while electromagnetic waves penetrate a certain dielectric material. Penetration depth was calculated using the following equation (Von Hippel 1954):

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

where c is the speed of light in free space (3×10^8 m/s). The efficiency of dielectric heating relies on the power input, working frequency, and dielectric properties of the target heating material. The power absorption in the material can be described as (Metaxas 1996)

$$P = 2\pi f \varepsilon_0 \varepsilon'' |\mathbf{E}|^2, \tag{3.}$$

where P is the power absorption in food in watts, ε_0 is the permittivity of free space, which is 8.854×10^{-12} F/m, and $\mathbf{E}$ is the electric field intensity in volts per meter.

Electromagnetic waves at specific frequencies were allocated for industrial, scientific, and medical (ISM) uses by the US Federal Communication Commission (FCC): 13.56, 27.12, and 40.68 MHz for RF and 915 and 2,450 MHz for microwave (ECFR 2017). The wavelength of electromagnetic waves at these specific frequencies and the penetration depth of waves in tap water at room temperature are shown in **Table 1**. Compared to microwaves, radio frequencies have the advantages of greater penetration depth and longer wavelength, which are more suitable for bulk material heating with better heating uniformity.

Measuring of Dielectric Properties

A dielectric property measurement system generally consists of a signal analyzer connected to a sample holder. The signal analyzers used for dielectric property measurements include LCR [inductance (L), capacitance (C), resistance (R)] meters, impedance analyzers, and spectrum/

Table 1 Comparison of major characteristics between radio frequency (RF) and microwave in the food industry

Characteristics	RF	Microwave
Working frequencies	13.56, 27.12, 40.68 MHz	915, 2,450 MHz
Wavelengths (in vacuum)	22.1, 11.1, 7.4 m	0.33, 0.12 m
Penetration depths (in tap water)	1.58, 0.79, 0.53 m	0.02, 0.01 m
Major heating mechanism	Ionic charge migration	Dipole water molecule agitation
System construction	Simple	Complicated

network/vector analyzers. For property measurements in 1–300 MHz, an LCR meter (works well for 5 Hz–3 GHz) (Izadifar & Baik 2008, Ozturk et al. 2016) or an impedance analyzer (20 Hz–3 GHz) (Boreddy & Subbiah 2016, Jeong & Kang 2014, Llave et al. 2014, Wang et al. 2003b) provide accurate results. Spectrum/network/vector analyzers work well for high frequencies (30 kHz–8.5 GHz) (Zhang et al. 2016, Zhu et al. 2014) but could also be used to measure at RFs with lower accuracy especially for low-moisture food products.

The dielectric properties of a food material, in general, change with its composition and temperature. Several studies have reported using a jacketed sample holder with a circulating oil/water system to control the sample temperature during dielectric property measurements (Guan et al. 2004, Wang et al. 2003b). Another common method of temperature control is placing the dielectric probe and sample holder in a heating/cooling chamber throughout measurement.

Radio-Frequency Heating Systems

RF-heating equipment can be generally divided into two types: the free-running oscillator (FRO) system and 50-Ω system (Awuah et al. 2014). A FRO RF system consists of a high-voltage transformer, a rectifier, an oscillator tube, a tuned circuit, an impedance coupling and matching circuit, and an applicator (**Figure 1*a***). The line power from the AC mains is transformed to a high voltage and converted into DC power by a rectifier. The oscillator uses a thermionic tube, which drives the resonant circuit to generate RF energy at a specific working frequency. RF energy is then transmitted to the product load placed between the electrodes, thereby generating heat within the load by dielectric loss. A 50-Ω RF system consists of a fixed-frequency crystal-driven oscillator (e.g., quartz), a solid-state amplifier, a dynamic automatic impedance matching network, and an applicator (**Figure 1*b***). The oscillator, amplifier, and matching network are connected with 50-Ω cables. The fixed-frequency crystal-driven oscillator can precisely control the frequency of the RF generator to produce a fixed output impedance (50 Ω). The impedance of the applicator with the

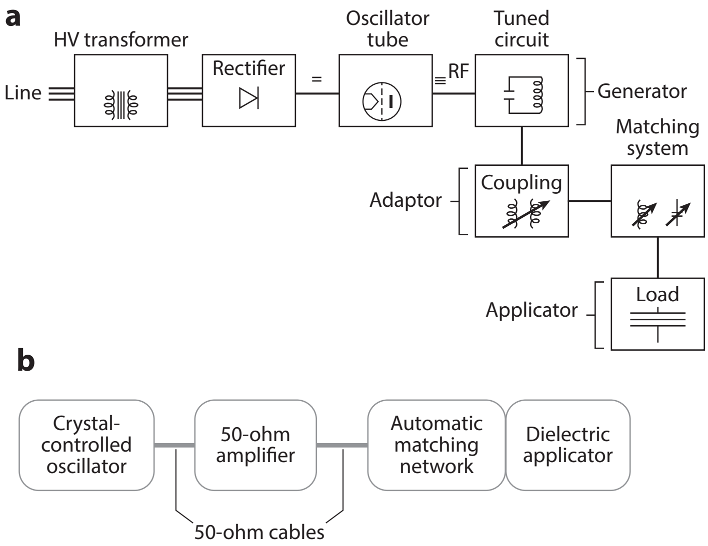

Figure 1

Scheme of (*a*) a typical free-running oscillator (FRO) radio-frequency (RF) system and (*b*) a 50-Ω RF system. Panel *a* adapted from Zhao et al. (2000) with permission from John Wiley and Sons. Panel *b* adapted from Awuah et al. (2014) with permission from CRC Press.

Table 2 **Comparison of free-running oscillator and 50-Ω radio frequency (RF) systems**

Characteristics	Free-running oscillator	50-Ω
Application	Most commonly used; more mature in the market with established knowledge	New technology; few applications in market
Cost	Low cost (∼50–75% of the cost of 50-Ω system)	High cost, using expensive tetrode tube, and a load impedance matching circuit with several variable vacuum capacitors
Complexity in installation and maintenance	Simple to set up, operate, and maintain	Requires specialist RF knowledge, particularly in matching the generator to the load
Flexibility	Can be used on various load dimensions and properties; more adaptable; dynamically match the load	Load impedance is matched to 50 Ω to maintain a fixed RF power level (accomplished by analyzing the phase and magnitude at the coaxial feed into the matching network); does not have the ability to change power according to changes in product moisture content
Power stability	Input power automatically matches the load, which has the advantage of selective heating, especially for drying	Constant power; does not adjust power automatically with variation of load moisture content

load is matched to 50 Ω to achieve maximum power transfer. The power consumption and voltage on the electrode system are displayed on the control panel.

The FRO system is the most common design of RF heater; 98% of all industrial-size RF heaters are based on this design. It is simple, flexible, and less costly than 50-Ω systems. The most popular application of FRO systems is in drying, e.g., cookies, crackers, textiles, paper, lumber, and glass fiber, because of its distinct moisture profiling characteristic. This characteristic is explained as RF energy focusing on wet areas more than dry areas to even out the moisture distribution in the food throughout the drying process. This moisture profiling property makes the FRO system highly preferable to the drying industry because it protects the food from being overheated during drying and reduces the variation in moisture content of the final product. As a result, FRO systems could reduce the cracking in cookies, control mold growth in the final product, prevent loss of volatile components due to the high drying temperature, and also allow a degree of separation between coloring and drying of the product, which is not possible with conventional drying. A 50-Ω system is a recently developed design of RF systems. It has a more stable frequency output because the matching system in the RF heater is automatically adjusted to maintain the load impedance at 50 Ω. It is suited for treating products with relatively stable moisture contents, such as in pasteurization and sterilization applications. The 50-Ω systems are more expensive than FRO systems and have not been popularly used by industries because of the complexity of set up and maintenance. **Table 2** summarizes the advantages and disadvantages of FRO and 50-Ω RF-heating systems. To conclude, the FRO system is a better choice for drying purposes, whereas the 50-Ω system is more suitable for food pasteurization/sterilization or chemical reactions because of accurate control of frequency and power and stable loads.

RADIO-FREQUENCY APPLICATIONS IN THE FOOD INDUSTRY

The applications of RF are introduced and summarized below based on their commercialization status or research progress (**Table 3**). We also summarize the active research groups in RF food processing/preserving for the readers' reference (**Table 4**).

Table 3 Summarization of radio frequency (RF) applications in the food industry from 2001 to 2016

Purpose	Material	Frequency	Power	RF system type	Bacteria species/log reduction	Treatment time and temperature	Reference
Bacteria inactivation	Wheat flour	27.12 MHz	6 kW	Free-running	*Salmonella* Enteritidis, *Enterococcus faecium*/3.7–5 log	15 min heat to 85°C, hold for 25 min	Liu et al. 2018
	Wheat flour	27.12 MHz	500 W	Free-running	*S.* Enteritidis, *E. faecium*/3–7 log	8.5–9 min heat to 75°C	Villa-Rojas et al. 2017
	Caixin	27.12 MHz	6 kW	Free-running	*Brassica campestris* L./0.23–4 log	5–30 min heat to 60°C	Liu et al. 2015
	Peach	27.12 MHz	15 kW	50 Ω	*Monilinia* spp./not provided	4.5 min heat to 35°C (sample in 40°C water)	Sisquella et al. 2014
	Nonfat dry milk	27.12 MHz	3 kW	Free-running	*Cronobacter sakazakii* and *Salmonella*/3 log	4.3–5.5 min heat to 75–90°C, hold for 13.6–75 min	Michael et al. 2014
	Pepper spice (black and red) with various water content	27.12 MHz	9 kW	Not provided	*Salmonella* Typhimurium, *Escherichia coli* O157:H7/5–6 log	34–42 s heat to 90°C	Jeong & Kang 2014
	Peanut butter cracker	27.12 MHz	9 kW	Not provided	*S.* Typhimurium, *E. coli* O157:H7/4.29–4.39 log (in creamy peanut butter), 4.55–5.32 log (in crunchy peanut butter)	90 s heat to 77–86°C (creamy peanut butter) 90 s heat to 78–90°C (crunchy peanut butter)	Ha et al. 2013
	Stone fruit	27.12 MHz	15 kW	50 Ω	*Monilinia* spp./not provided	9 min heat to 42–45°C (sample in 20°C water)	Sisquella et al. 2013
	Apple juice	20 to 60 kHz	25 kV/cm	Not provided	*E. coli*/0.8, 7.3, and 6.6 log	1.6 s to 25, 55, and 75°C (depending on the voltage supply)	Ukuku & Geveke 2012
	Pepper spice (black and red)	27.12 MHz	9 kW	Not provided	*S.* Typhimurium/3.38–5 log *E. coli* O157:H7/2.80–4.29 log	40 s heat to 60°C 50 s heat to 60°C	Kim et al. 2012

(Continued)

Table 3 *(Continued)*

Purpose	Material	Frequency	Power	RF system type	Bacteria species/log reduction	Treatment time and temperature	Reference
Bacteria inactivation	Almonds	27.12 MHz	6 kW	Free-running	*Salmonella*/5 log	2–4 min heat to 75°C, hold for 1.5 min	Gao et al. 2011
	Enriched white bread	27.12 MHz	6 kW	Free-running	*Penicillium citrinum*/4 log	4.6 min heat to 58°C	Liu et al. 2011
	Peach and nectarines	27.12 MHz	15 kW	50 Ω	*Monilinia* spp./not provided	18 min heat to 62.5°C	Casals et al. 2010
	Soy milk	28 MHz	1 kW	Not provided	*Bacillus subtilis*/4 log	0.4 s heat to 115°C, hold for 10 s	Uemura et al. 2010
	Meat (comminuted)	Not provided	0.5 kW	Not provided	*Bacillus cereus*/5.4 and 1.8 log *Clostridium perfringens*/6.8 and 4.1 log	33 min heat to 67.6–76°C, hold for 2 min (Sample in water)	Byrne et al. 2010
	Apple cider	5–65 kHz	0.15–15 kV/cm	Not provided	*Lactobacillus plantarum*/2.5–3.1 log	17 ms heat to 45–55°C, hold for 5–50 s	Geveke et al. 2009
	Apple cider	15–70 kHz	80 kW	Not provided	*E. coli* K12/4.8 log	140–420 μs heat to 60°C	Geveke & Brunkhorst 2008
	Orange juice	20, 30, and 40 kHz	80 kW	Not provided	*E. coli* K12/2.1 and 3.3 log	270 μs heat to 60°C, 65°C, hold for 3 s	Geveke et al. 2007
	Ground beef	27.12 MHz	1.5 kW	Not provided	*E. coli* K12/7 log	4.25 min heat to 72°C	Guo et al. 2006
	Fish meal	6–14MHz	0.17–1.2kW	Free-running	*Salmonella* spp./3.3–6.2 log *E. coli* O157:H7/3.1–5.3 log	1–2 min heat to 70–90°C, hold for 1 min	Lagunas-Solar et al. 2005
	Phosphate buffer and mashed potatoes	27.12 MHz	6 kW	Free-running	*Clostridium sporogenes*/7 log	22 min heat to 121°C, hold for 2.4–7.3 min	Luechapattanaporn et al. 2004
	Ham	27.12 MHz	0.6 kW	50 Ω	Not provided	5 min heat to 75°C, 85°C, hold for 5 min	Orsat el al. 2004

(*Continued*)

Table 3 ***(Continued)***

Purpose	Material	Frequency	Power	RF system type	Bacteria species/log reduction	Treatment time and temperature	Reference
Bacteria inactivation	Apple juice	15–70 kHz	4 kW	Not provided	*E. coli* K12/3 log	0.17 ms heat to 50°C	Geveke & Brunkhorst 2004
	Suspension of *Saccharomyces cerevisiae* in water	20 to 60 kHz	1 kW (20–30 kV/cm)	Not provided	*S. cerevisiae*/0.8, 2.1, and 4.7 log	3 s heat to 35°C, 40°C, 55°C	Geveke & Brunkhorst 2003
	Apple cider, beer, deionized water, liquid whole egg, and tomato juice	18 MHz	19 kW	50 Ω	*E. coli* K-12 *Listeria innocua*/1.2–2.0 log	9 s or 4.2 min heat to 45°C and 50°C	Geveke et al. 2002
	Alfalfa seed	39 MHz	3 kW	Not provided	*Salmonella* *E. coli* O157:H7/0–1.5 log	0–28 s heat to 50–126°C	Nelson et al. 2002
Disinfestation	Rice (milled)	27.12 MHz	6 kW	Free-running	NA	4.3 min heat to 50°C, hold for 5 min	Zhou et al. 2015
	Lentils	27.12 MHz	6 kW	Free-running	NA	5.5 min heat to 60°C, hold for 10 min	Jiao et al. 2011
	Legumes	27.12 MHz	6 kW	Free-running	NA	5–7min heat to 60°C, hold for 10 min	Wang et al. 2010
	Walnut	27.12 MHz	25 W	Free-running	NA	heat to 52–60°C, hold for 5 min	Wang et al. 2007b
	Walnuts (in shell)	27.12 MHz	6 kW	Free-running	NA	3 min heat to 54°C, hold for 5 min	Wang et al. 2001
Cooking	Beef (ground)	27.12 MHz	6 kW	Free-running	NA	4.08–18.87 min heat to 60°C (sample in 10, 25 and 50°C water)	Nagaraj et al. 2015
	Egg white dispersion	27.12 MHz	2 kW	50 Ω	NA	1–3 min heat to 92°C	Ahmed et al. 2007
	Meat emulsion (comminuted)	27.12 MHz	0.2–0.6 kW	50 Ω	NA	12 min heat to 73°C (sample in water)	Lyng et al. 2007
	Pork ham	Not provided	0.45–0.55 kW	Not provided	NA	42 min heat to 73°C, hold for 2 min	Zhang et al. 2006

(Continued)

Table 3 *(Continued)*

Purpose	Material	Frequency	Power	RF system type	Bacteria species/log reduction	Treatment time and temperature	Reference
Cooking	Pork (comminuted)	Not provided	0.45 W	Not provided	NA	7.7 min and 2 min heat to 73°C (sample in room temperature water and 90°C water)	Brunton et al. 2005
	Turkey breast rolls	Not provided	0.5 kW	Not provided	NA	40 min heat to 73°C	Tang et al. 2005
	Meat (comminuted)	Not provided	0.45–0.55 kW	Not provided	NA	25–35 min heat to 74–80°C, hold for 1–3 min	Zhang et al. 2004
	Beef (ground, 2% salt, comminuted, muscle)	27.12 MHz	1.5 kW	Not provided	NA	5.83, 13.5, and 13.25 min for ground beef, comminuted meat, and muscle, respectively, heat to 72°C	Laycock et al. 2003
Thawing	Pork	27.12 MHz	800 W	Not provided	NA	16 min heat to 0°C	Kim et al. 2016
	Tuna fish	13.56 MHz	1 kW	50 Ω	NA	39.8, 32.4, 31.6, 30.5, 30.0 min heat to −3°C	Llave et al. 2014
	Beef	27.12 MHz	0.6 kW	50 Ω	NA	20–45 min heat to 0°C	Farag et al. 2009
Enzyme inactivation	Miso paste	Not provided	Not provided	Not provided	NA	Heat to 72 °C	Uemura et al. 2014
	Apple	27.12 MHz	3.5 kW	50 Ω	NA	3 min heat to 98°C, hold 30 min at room temperature	Manzocco et al. 2008
	Myrosinase (in white mustard)	13.5 MHz	Not provided	Not provided	NA	Heat to 112°C	Schuster-Gajzago et al. 2006
Roasting	Peanut	27.12 MHz	12 kW	Free-running	NA	45 min heat to 110–130°C	Jiao et al. 2016
Drying	Macadamia nuts	27.12 MHz	12 kW	Free-running	NA	20–120 min heat to 50–80°C	Wang et al. 2014

Abbreviation: NA, not available.

Table 4 Active research groups in the radio frequency (RF) food heating area

Institute	Major researchers/ principal investigators	Main research direction
Washington State University, USA	Juming Tang	Low-moisture food pasteurization, packaged food pasteurization/sterilization, and agricultural material disinfestation
University College Dublin, Ireland	James G. Lyng	Meat cooking and pasteurization
University College Dublin, Ireland	K.W. Farag	Meat thawing/tempering
University of Nebraska-Lincoln, USA	Jeyam Subbia	Agricultural product (milk/egg powder) pasteurization, and computer modeling
Northeast Agricultural and Forest Technology University, China	Shaojin Wang	Agricultural product disinfestation, pasteurization, drying, and enzyme inactivation
Università Degli Studi di Salerno, Italy	Marra Francesco	Computer modeling of RF-heating process
Tokyo Ocean University, Japan	Noboru Sakai	Fish thawing/tempering
Seoul National University, Korea	Dong-Hyun Kang	Dry spice pasteurization
IRTA, Spain	J. Usall	Fruit disinfestation
China Agricultural University, China	Yanhong Liu	Agricultural product drying
Food Industry Research and Development Institute, Taiwan	Chung-Liang Chu, Meng-Jen Tsai	Industrial RF drying of agricultural products
National Ilan University, Taiwan	Su-Der Chen	RF treatment on rice, drying of agricultural products and fermented biomasses
University of Saskatchewan, Canada	Oon-Doo Baik	Postharvest pest control and biomaterial processing
Shanghai Ocean University, China	Yang Jiao	Thawing and drying of fish and meat
Shanghai Jiaotong University, China	Shunshan Jiao	Roasting, pasteurization, and disinfestation of agricultural products
University of Georgia, USA	Fanbin Kong, Rakesh Singh	RF control of pathogen in low-moisture foods

Commercialized Application

Biscuit postbaking is one of the RF applications that has been successfully commercialized in the food industry. Some commercial RF thawing equipment is also available in the market for frozen meat/fishery product tempering.

Postbaking. RF postbaking has been commercially utilized in the biscuit industry for postbaking for more than 50 years. Checking is an industry term and refers to a phenomenon that describes biscuit product cracks due to the differential of stresses at different locations. The stress difference is caused by uneven removal of moisture and consequent shrinkage at different locations within a single biscuit during baking. The introduction of RF postbaking into the cracker or biscuit production line reduces checking from approximately 50% to almost 0% (Holland 1963). Meanwhile, RF heating increases the throughput by up to 40% because the RF energy penetrates the insulating outer crust of the product to remove water from the high-moisture center zone of the product. Few recent publications can be found regarding the postbaking application because it was fully commercialized by the 1960s (Holland 1963, 1966).

Thawing/tempering. Traditional thawing/tempering is normally done via circulating or still air in a cooling room (4°C). This method has the long-lasting problem of slow thawing, which may take days depending on the size of the frozen packages. Lengthy thawing causes significant drip losses and also results in bacteria growth and product quality degradation. Attempts were made during the 1940s to explore the capability of RF thawing in, e.g., frozen meat, fish, and vegetables, but the systematic results were not reported in the published literature. Commercial RF thawing/tempering lines were quickly established for industrial use after these trials. Although commercial RF thawing/tempering equipment has been used for decades, only in recent years was finer research published on meat and fish thawing/tempering with experimental scale 50-Ω RF machines to meet the rising needs for food safety, reduce food waste, and provide high-quality products for the consumer market.

Farag et al. (2008) used a self-constructed RF heater (27.12 MHz, 500 W) to temper a 4-kg beef block from −20°C to −3.6°C. The results showed that RF tempering reduced the time taken by traditional methods from 50 h to 35 min. The results also suggested that improving the homogeneity of sample composition could enhance thawing uniformity. Further study was conducted to evaluate the quality parameters of beef defrosted by RF and conventional methods. Results showed a significant reduction of drip loss and micronutrient loss in RF-defrosted meat compared to air-thawed product (Farag et al. 2009). Based on the experimental results of Farag et al. (2008), Uyar et al. (2015) constructed a mathematical model to predict the heating pattern of the meat block in RF thawing with different electrode gap conditions. By comparing the temperature profile with experimental results, it was concluded that the developed model was capable of predicting temperature distribution in food during RF treatment.

Llave et al. (2014) determined the dielectric properties of frozen tuna in the tempering temperature range and studied the efficacy of RF tempering of a frozen tuna block. Results showed a threefold reduction in thawing time compared with the traditional thawing method and that using an electrode size comparable to the sample surface achieves the best heating uniformity.

Several companies based in Italy, the United Kingdom, France, the United States, and Japan have produced commercialized RF systems for defrosting/tempering. For example, Stalam (Italy) produces RF tempering/defrosting equipment with a power of ∼3–85 kW for meat, fish, and vegetable tempering. It has a maximum throughput of 2,500 kg/h when tempering frozen meat from −25°C to −5°C. Yamamoto Vinita (Japan) manufactures ∼5–120 kW high-frequency tempering machines using 13.56-MHz RF waves that have a throughput of ∼60–4,000 kg/h on thick meat blocks.

RF thawing/tempering techniques are now commonly used in industry but are limited to regular (or approximately regular)-shaped fish and meat. More research must be done to solve the irregular-shaped-food thawing problems, which may largely extend RF thawing applications.

Partially Commercialized Applications

RF drying equipment, often combined with vacuum drying, is commercially used in the wood, textile, and paper industries. Because of the complexity of food composition, the technology has not been readily applied in the food industry. Extensive research has been conducted over the past 20 years on the use of RF on postharvest pest control in agriculture products, leading to well-established knowledge and successful commercial applications. So far, the use of RF heating in general food processing is limited, and more systematic research from benchtop to pilot scale systems is needed. Capital cost, electric power consumption, and proper training for operations are the major concerns of food manufacturers in adopting the technology.

Drying. RF heaters are often used during the final stages of drying to improve energy efficiency and product quality. The conventional hot-air drying methods for solid or semisolid foods are inefficient at removing moisture from the product during the falling rate period. Furthermore, conventional drying happens from the outside to the inside of the food and normally results in cracks or hard shells in the final products. RF drying could overcome these two major disadvantages of hot-air drying with its unique selective and volumetric heating properties. When putting a moist material into an RF-heating cavity, the water molecules tend to absorb more energy than the solids because of the differences in their dielectric properties. Thus, the food quality could be protected by evaporating only the water, and the food itself would be only minimally heated. However, the operating cost of solely using RF drying is usually not economically viable in the food industry where high throughputs are concerned. Thus, the combination of intermittent/periodic RF with hot-air drying methods was explored and utilized. The combination maximizes each technology's strengths and minimizes each technology's limitations.

Porterfield & Wright (1971) conducted research on RF drying of peanuts. They determined the influencing factors on the power absorption in the peanut bulk and also compared the drying rate of RF with other typical drying methods. The authors concluded that the bulk volume, moisture content, and electrode distance influenced the power absorption during RF heating, and the internal heating characteristic of RF could increase the drying efficiency when combined with hot-air drying.

Jumah (2005) conducted a computer simulation of RF-assisted fluidized bed drying of grains to study the effect of time-varying RF heating and the key operating parameters. The model built in this study has been used to predict the drying curves and suggested that intermittent RF assistance could improve the product quality of heat-sensitive material in a fluidized bed dryer.

Wang et al. (2014) compared the hot-air drying effect with and without RF on macadamia nuts. The authors concluded that adding RF to the hot-air drying process could shorten the drying time by half, but the product quality of the two processing methods was not significantly different. As a follow-up, this group conducted another set of experiments in 2014 to evaluate the nut heating uniformity during RF and hot-air-assisted RF drying. The authors divided the single container into 12 compartments and tested the temperature distribution and weight loss after drying in each compartment. It was found that the heating rate at the corner of the container is higher than at the center because the electric field intensity is higher at the edges. Moving samples on a conveyor belt does not significantly improve heating uniformity.

Although RF drying is widely commercialized around the world in the wood, textile, and paper industries, as well as in the postbaking of biscuits, not much research has been done on food drying. This is mainly because most food products, especially agricultural commodities, can be spread to form thin-layers; thus, hot-air drying produces reasonable quality products and is more cost effective in most situations. In addition, RF systems are too costly for drying large-volume agricultural commodities, such as grains. Thus, RF drying could benefit by providing high-quality final products for high value–added products, especially in applications in which the same effect cannot be achieved by conventional means. Moreover, RF drying can be cost effective where space is limited. For example, on cookie/cracker lines with RF, up to a 40% increase in throughput can often be obtained. Achieving this increase with conventional means would often require the drying line to be extended by 30–40%. However, although combining RF and hot-air drying is perfect in drying theory, it has been found by many RF equipment manufacturers that RF and hot-air drying have conflicting requirements, which gives rise to many problems in certain applications. In those cases, the combined drying equipment becomes less cost effective and more unreliable.

Disinfestation. The importation and exportation of agricultural products can cause pest invasion and infestation, which are major concerns to many countries. Chemical methods (fumigation) are the current prevailing disinfestation methods, which are effective and less costly, but are banned in many countries. Thus, many biological and physical methods are under development to inactivate pests more efficiently and in a more environmentally friendly manner. RF heating can selectively heat and kill the pests without damaging the agricultural product with its distinct selective heating mechanism.

The Radyne company (UK) tried many applications of RF-heating technology, including the RF disinfestation method especially for tropical countries. But detailed research results were not reported until Nelson (1996) first investigated the dielectric properties of pests and found that the field intensities in pests and their hosts are different. Since 1997, a research team at Washington State University (USA) and its collaborators (Mitcham et al. 2004; Tang et al. 2000; Wang et al. 2002, 2003a) have conducted comprehensive research to bridge knowledge gaps necessary for developing RF disinfestation treatments. Their studies have led to experimental data for dielectric properties of a wide range of pests and their host agricultural materials over a wide temperature range (Guo et al. 2010, Jiao et al. 2011), to understanding of the thermal death lethality of pests in different life stages (Armstrong et al. 2009, Wang et al. 2009), to pilot-scale validation on the effectiveness of RF disinfestation in industrial facilities (Wang et al. 2007a,b), and to the improvement of RF disinfestation uniformity using computer simulation (Tiwari et al. 2011). The RF disinfestation method would be mostly applied to grains, nuts, and dried fruits because of the insensitivity of dry foods to heat compared to fresh fruits and vegetables (Hou et al. 2016, Wang et al. 2003a).

Studies have been conducted on inactivation of pests in fish meal (Lagunas-Solar et al. 2005), legumes (Jiao et al. 2012, Wang et al. 2010), coffee beans (Pan et al. 2012), stored wheat (Shrestha et al. 2013), milled rice (Zhou et al. 2015), and nuts (Hou et al. 2015). Moving, mixing, and hot-air assisted methods were applied to improve the temperature uniformity within the food volume. The research showed no significant product quality degradation after RF treatment when reaching 100% insect lethality, which demonstrates the potential of industrializing RF disinfestation. A scale-up study was conducted by Wang et al. (2007a,b) in which boxes containing 11 kg of infested walnuts were each treated in a 27-MHz, 25-kW industrial-scale continuous RF system. The system raised the temperature to 60°C over 5 min, and the treatment resulted in 100% mortality of the infested insects and walnut quality was not affected negatively during a two-year storage test. The average heating efficiency is estimated to be 79.5% when treating walnuts at 1,561.7 kg/h, and the cost is comparable to that of fumigation methods. The above research results demonstrated that RF disinfestation technologies hold great potential for industrial applications, especially in tropical countries. Recently, RF systems have been commercialized for postharvest disinfestation of agriculture products, including rice, in Thailand (Ureka Agro Machinery; **http://www.eurekaagro.co.th**). But most commercial applications for disinfestation are taking place in private companies, which often choose not to inform the general public.

Still Under Development

Owing to the more stringent regulatory requirements for food safety in recent years, RF pasteurization/sterilization has drawn attention from both academia and the food industry. In addition, RF is also researched in agricultural products for roasting and blanching, but the literature is still limited.

Pasteurization/Sterilization. RF pasteurization/sterilization technologies were developed to ensure food safety and extend product shelf life. RF heating can penetrate the food package and elevate the food temperature to the target temperature much faster than traditional hot water pasteurization/sterilization, which allows in-package pasteurization/sterilization and prevents further cross contamination. Reducing the heating time significantly improves the food quality. However, to guarantee microorganism inactivation, the temperature at cold spots must be monitored at all times to guarantee lethality.

Nelson et al. (2002) used RF heating to reduce three different pathogens in alfalfa seeds. However, the desired 5-log pathogen reduction was not achieved without affecting germination. The US Department of Defense (DoD) supported a research project at Washington State University to explore the application of RF heating for the production of shelf-stable military group rations in large polymeric trays. In this project, Wang et al. (2003c) developed a pilot-scale RF food sterilization system to process a six-pound military group ration tray containing macaroni and cheese. A model food with a chemical marker was developed to simulate the macaroni and cheese and reveal the heating pattern. The results showed that 30 min of RF heating could achieve an $F_0 = 10$ min lethality, which could be achieved only by a 150-min retort process. Luechapattanaporn et al. (2004) verified the efficacy of RF sterilization of mashed potato in the six-pound trays using a microbial surrogate *Clostridium sporogenes* (PA 3679). But the same group faced challenges in developing a continuous RF system that has the capacity of applying two atmospheres overpressure while allowing continuous loading and unloading of prepackaged foods. Lack of further DoD support forced the Washington State University team to halt the project. But using RF for microorganism inactivation in various food commodities, e.g., peaches/nectarines/stone fruits (Casals et al. 2010; Sisquella et al. 2013, 2014), ground beef (Schlisselberg et al. 2013), peanut butter cracker sandwiches (Ha et al. 2013), and packaged vegetables (Liu et al. 2015), has since been widely researched. RF energy has also been studied for liquid food pasteurization of, e.g., milk (Awuah et al. 2005), orange juice (Geveke et al. 2007), apple juice/cider (Geveke & Brunkhorst 2004, 2008; Geveke et al. 2009), and soy milk (Uemura et al. 2010) and found to provide enhanced product quality and processing efficiency.

In recent years, several research groups, including those at Washington State University, University of Georgia (USA), and Seoul National University (Korea), have been investigating the potential of RF for pathogen control in bulk low-moisture foods and ingredients. Because of the low thermal diffusivity of low-moisture foods, conventional methods for bulk heating of low-moisture foods are slow and inefficient. RF has the unique advantages of volumetric heating and penetration depth and can replace the conventional methods for pathogen control. Research has been conducted that combines the knowledge of the thermal kinetics of pathogen in low-moisture foods with water activity (Syamaladevi et al. 2016a,b; Villa-Rojas et al. 2013) in developing RF pasteurization for almond, spices, and peanut butter crackers (Gao et al. 2011, 2012; Ha et al. 2013; Jeong & Kang 2014; Kim et al 2012). Significant research also addresses the issue of heating nonuniformity in low-moisture foods during RF pathogen control (Jiao et al. 2014, 2015).

A major challenge in developing thermal treatments for pathogen control in low-moisture foods is that low water activities make bacterial pathogens, e.g., *Salmonella*, extremely heat tolerant. Syamaladevi et al. (2016a) and Tadapaneni et al. (2017) developed a special apparatus for measuring the water activity change at different temperatures to understand the relationship between the water activity and the pathogen kinetics during temperature elevation in RF pasteurization. Villa-Rojas et al. (2017) conducted experiments of wheat flour (water activity 0.25, 0.45, and 0.65) inactivation tests on a benchtop-scale RF system, and found that a ~5–7-log *Salmonella* reduction can be achieved after ~8.5–9 min of RF treatment. Furthermore, Liu et al. (2018) validated the efficacy of using RF to inactivate *Enterococcus faecium* in wheat flour (water activity 0.45) with a surrogate of *E. faecium* on a pilot-scale RF system. A 39-min RF treatment (6 kW, 27 MHz) is sufficient to inactivate pathogen surrogates in 3-kg wheat-flour samples. This series of research in low-moisture food indicates that in spite of the fact that pathogens in low-moisture foods are much more difficult to inactivate than in a high-moisture environment, RF heating can be effective in inactivating pathogens in low-moisture conditions (Liu et al. 2018).

Roasting. Jiao et al. (2016) studied hot-air-assisted RF roasting of salted peanuts with a 12-kW, 27.12-MHz RF system for 45 min at 110–130°C. The volatile components and oxidation values were analyzed before and after treatment and also during storage for 13–15 weeks for comparison. It was found that RF has high roasting efficiency and improves the product quality and shelf life.

Enzyme inactivation (blanching). Enzyme inactivation, also called blanching in vegetable and fruit processing, is a vital preservation step before food storage. Schuster-Gajzago et al. (2006) researched the enzyme inactivation of myrosinase in white mustard to remove the spicy flavor at 112°C in a 13.5-MHz RF machine. They reported that RF energy can be used to develop a low-cost and environmentally friendly thermal process for enzyme inactivation and could effectively produce a product with acceptable sensory properties.

Manzocco et al. (2008) studied RF blanching of whole apples at 6.2 kV for 3 min and compared the enzyme inactivation effects with traditional water-blanched apple cubes. The results showed RF could effectively inactivate the oxidizing enzymes under proper operating conditions and preserve more sweetness in apples. RF blanching saves energy and time and also reduces the cost of waste management. Uemura et al. (2014) reported that enzymes in miso paste could be completely inactivated at 72°C by RF heating, which is 12°C lower than traditional methods. The RF treatment also reduced the processing time to one-third of the conventional heating.

Although it has many benefits, such as shorter processing times and reduced water usage, the capital cost of the equipment and the lack of systematic research in experiment development are still the largest obstacles for commercial uses of RF heating in blanching.

Discussion: limitations/barriers for industrial applications. RF heating has been proven as an effective method in many food safety applications in research laboratories, but several limitations hinder the industrial applications. The primary barrier is still the nonuniformity of heating, especially in heterogeneous food material with irregular shape. The food product caused changes of the original RF field distribution in the RF cavity, which results in nonuniform heating. Because of the distinct heating mechanism, there are many factors influencing the temperature distribution and heating uniformity, including the food composition and size and the shape of the load. Unlike traditional heating from outside to inside, the temperature differences inside a food matrix can be unpredictable. Secondly, it requires more training and experience for the food technologist and/or operator to properly operate RF-heating systems. Understanding the mechanism and troubleshooting take time and effort, which can be seen as an additional cost of implementing the RF technology.

COMPUTER MODELING

Computer simulation has been an effective tool to help understand electric field distribution and heating uniformity in RF systems. Computer modeling techniques have advanced greatly in the twenty-first century because of rapid increases in computation power and improvements in commercial software. We report here on the progress of computer simulations related to RF heating in food applications.

Yang et al. (2003) used a computer program package TLM-FOOD-HEATING to simulate the RF-heating process (1 kW, 35 MHz) on radish and alfalfa seeds. The electromagnetic problem was solved by TLM (transmission line method) and heat diffusion was solved by the FDTD (finite difference time domain) method. The differences between experiment and simulation results in radish seeds were 1.8, 1.1, 8.9, and 13.6°C at the center, top, edge, and bottom locations, respectively, and 0.9, 2.4, 7.8, and 14.3°C in alfalfa seeds, respectively, when being heated from

25°C to 80°C. It was found that the simulation result had a larger error at the edge and bottom locations. The author claimed this difference was due to the insufficient description of the boundary conditions. Chan et al. (2004) used a finite element method (FEM)-based commercial package, HFSS (high-frequency structure simulator), to solve the coupled equations in an RF-heating process (6 kW, 27 MHz) of a 1% CMC (carboxymethyl cellulose) solution. By comparing the reflection coefficient (S11), phase, and heating patterns for loads with different shapes, sizes, and positions, a good agreement between the experiment and the simulation was found. However, the heating pattern of the CMC solution was only compared with the electric field pattern from the simulation. Thus, only a general conclusion was drawn describing the discrepancy between experiment and simulation results. Jumah (2005) developed a mathematical model for RF-assisted fluidized bed drying of grains and solved the partial differential equations. Various frequencies and electric field strengths were tested for temperature and moisture content change during drying. However, the simulation considered the food load as a uniform temperature point, so no heating uniformity tests were conducted.

Within the past decade, comprehensive studies were conducted by researchers with the FEM-based software COMSOL Multiphysics® (previously named FEMLAB). In these studies, a quasistatic assumption was made because the alternation of the electric field and the power conversion from electromagnetic energy to heat are much faster than that of heat transfer in a time step. The use of COMSOL Multiphysics® largely simplified the modeling process and reduced the computing time.

Marra et al. (2007) developed a computer simulation model to simulate meat batter being subjected to RF cooking. The simulation results were validated by experiments with a 50-Ω system (600 W, 27.12 MHz). The results showed that an uneven temperature distribution existed in a cylinder of meat batter. The bottom of the cylinder had a higher heating rate than the upper part; a higher applied power may result in a more uneven temperature distribution.

Romano & Marra (2008) carried out a numerical analysis with FEMLAB 3.1 on RF heating (27.12 MHz) of regular-shaped meat patties. Sample shape (cube, cylinder, and sphere), orientation (horizontal and vertical), electrode distance, sample/oven volume ratio, and sample surface exposed in the electrode were chosen as the influencing factors to test the effect on heating rate and uniformity. The results showed that the sample shape influenced the heating rate and uniformity and that for a cylinder product the vertically oriented position may achieve a better heating uniformity. It was also found that the absorbed RF in foods were relatively stable during 100-W and 200-W RF treatments, within the efficiency range of 40% to 60%. But the absorbed RF varied between 20% and 60% at 300 W and 400 W. The sample with a sphere shape had the lowest power absorption among all the shapes, followed by a horizontally placed cylinder.

Wang et al. (2008) developed and solved a mathematical model using COMSOL Multiphysics® to study the influence of dielectric properties on mashed potatoes and circulating water subjected to RF heating (6 kW, 27.12 MHz). Several representative locations inside the mashed potato samples were chosen for comparison between the experiment and simulation results; the differences between the highest and lowest temperature were <12°C while the center temperature rose from room temperature to 55°C. The authors also found the relationship between loss factor and heating rate was not positively linear from both experiments and simulations. Tiwari et al. (2011) developed and validated a model for wheat flour using the COMSOL Multiphysics® software package in RF heating (12 kW, 27.12 MHz). The temperature distribution of flour in a rectangular box from both simulation and experiment showed good agreement. Dev et al. (2012) conducted computer simulations with FEMLAB 3.4 for in-shell eggs with different orientations and electric field strengths in a 600-W, 27.12-MHz, 50-Ω RF system. Maxwell's equations and Fourier's equation, which govern the electromagnetic field and heat transfer, respectively, were solved to obtain the temperature distribution in eggs. Experiments were conducted with a mock egg with a transparent shell to validate the heating process, and the nonuniform heating was observed through the coagulation of the egg white. Simulation and experiment results were in good agreement and showed that rotation improved the heating uniformity. Alfaifi et al. (2014) developed and validated an RF-dried fruit disinfestation model using the COMSOL Multiphysics® package (6 kW, 27.12 MHz). The temperature profile agreed well with simulation results in most places, but at the corners there was a difference of 7°C. A sensitivity study was conducted and showed that dielectric properties and electrode voltage are the two major influencing factors to heating uniformity. Chen et al. (2016) simulated the conveyor belt movement during RF heating. The authors assumed an RF power ratio as a function of heating time and sample position during movement. Huang et al. (2016a) researched the influence of container thickness on RF-heating uniformity using COMSOL Multiphysics® modeling.

The literature shows that the heating pattern of food subjected to RF can be predicted by computer modeling if parameters and conditions are properly set. Computer modeling has been proven to be an efficient tool to demonstrate the electric field and temperature distribution, test new strategies, optimize parameters, and design appropriate RF treatment conditions as well as to help develop heating uniformity improvement methods.

CURRENT ISSUES

Arcing

Arcing (flashing) can be a potential problem in all RF and microwave processing and is not well understood by many RF researchers or by industrial users of RF equipment. Arcing generally occurs when the RF voltage between two points exceeds the voltage that those points can withstand without causing the material separating them (usually air or product) to break down. The energy contained in such a sustained arc is more than sufficient to set the product on fire as well as to cause burning of the conveyor band and melting of the electrode plates and other components. Therefore, a suitable arc detection system should always be employed in all RF equipment. However, this is not always incorporated by all manufacturers in practice.

Arcing is mainly caused by the following: (*a*) The voltage field is too high (greater than the breakdown voltage of air) for the equipment. The voltage across the electrode system varies as the gap between the electrodes changes. For a constant product height, if the electrode gap is increased, then, due to the potential divider effect across the air gap, a significantly higher voltage is needed to induce the necessary electric field strength across the product to obtain the heating effect. To prevent this from happening, the electric potential should be lowered by reducing the air gap between sample and electrode or by adding an extra circuit to divide the voltage. (*b*) There is excessive humidity in the air between electrodes. Removing the excessive RF field quickly, especially during the drying process, is important to avoid arcing. (*c*) Poorly presented product may allow RF current to flow through an unexpected short-cut in the RF cavity. The RF current flowing through the product is essentially going to follow the path of least resistance between the electrode plates. If potential paths of varying resistances are provided, then the heating effect is greatest along the path with the lowest resistance. Therefore, it is essential to make the product as homogeneous as possible in composition and size (especially height).

Nonuniform Heating

Nonuniform heating remains a critical problem in the food industry. Food materials are more heat sensitive than are textiles or wood; thus, they require better heating uniformity to reduce quality

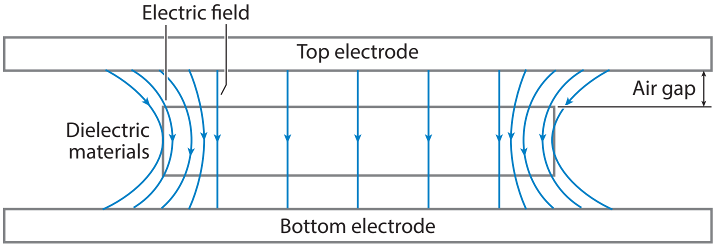

Figure 2

The electric field strength between two parallel plate electrodes with a dielectric sample slab placed in the center and middle in a radio-frequency heater cavity showing fringing field at the sample edges. Figure adapted from Huang et al. (2016b) with permission from Elsevier.

losses. Due to the intrinsic properties of the dielectric material, fringing field formation around and inside the food product is the cause of nonuniform heating in foods (**Figure 2**) (Margulies 1983). To balance out the fringing field effect, researchers developed uniformity improvement methods suited to different products.

Mathematical modeling techniques to assist heating uniformity improvement have been developed largely over the past two decades. These techniques, combined with new experiments and improved equipment design, have resulted in improved heating uniformity. More work is needed to scale up laboratory results to sizes suitable for industrial applications.

CONCLUSION

RF heating is a unique means of volumetric heating for agriculture and food products and holds the potential to address emerging food safety concerns associated with high- and low-moisture foods. But RF heating of food materials is complicated. Many factors influence heating uniformity and industrial scale-up. These factors can be incorporated in sophisticated computer simulations aided by ever-increasing computational powers. The influences of these factors can be validated by pilot-scale testing to facilitate the design of industrial processes. Our past 20 years of experience have taught us an important lesson: Fragmented research conducted by academic researchers in isolation is not effective. Close collaboration between academic researchers and RF engineers, equipment manufacturers, and food processing companies, persistent systematic research, and new technological developments are needed to further bridge the gaps between academic research and industrial applications.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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