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Advances in Food Processing Through Radio Frequency Technology: Applications in Pest Control, Microbial and Enzymatic Inactivation

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Abstract
Foodborne illnesses occur due to contamination by pathogenic microorganisms. Therefore, decontaminating food is vital before marketing and circulation. Radio frequency (RF) heating stands out in several branches of industry, mainly food processing, as an alternative method to conventional pasteurization which takes long process times and overheating. RF heating functions without relying on heat conduction. It generates internal heat by inducing the rotation of polar molecules and the motion of ions. The advantages of dielectric heating with greater wave penetration include rapid, uniform and volumetric heating, presenting high energy efficiency. Furthermore, it is an effective, validated method for eliminating pathogens in agricultural products and is free from chemical residues. Although many reviews have discussed this technology, few reviews have covered the research trends in this field in the recent years, during which the number of studies discussing RF treatment of foods have increased. Therefore, this review focuses on the RF applications in the food industry for pest control, microbial and enzymatic inactivation of solid, liquid, and powdered foods in the last five years. Besides covering the fundamental aspects of RF technology, we also examine its benefits and drawbacks, address the challenges it presents, and explore future prospects

Keywords Radio frequencies · Food safety · Heating uniformity · Microbial inactivation · Pasteurization · Thermal processing

Introduction

The expansion of formulation engineering within the food processing industry, coupled with the demand for diversified food products, has spurred significant advancements in the food ingredients market. Many of these ingredients are manufactured in a powdered form, underscoring the vital role of powder processing technology for both food producers and food ingredient manufacturers [1]. Powdered foods have low bulk weight, making transportation and storage easier [2]. Furthermore, reducing moisture content reduces the rate of quality degradation. Food powders have low water activity (a_w) with values equal to or less than 0.7 [3]. In this sense, it was expected that powdered foods would be safe from a microbiological point of view. Later, researchers reported that rehydrating powdered foods contaminated with microorganisms helped repair lesions from the spores resulting in deadly *Enterococcus* outbreaks in powdered milk [4]. Contaminated food powder retards microbial growth. However, microorganisms survive for a long time. Thus, sterilization techniques aimed to inactivate microbial cells in solid and liquid foods through denaturation of DNA at 71.06 °C for 15 s followed by drying with hot air at 135 to 205 °C for 5–6 s [5]. Nevertheless, the elevated temperatures used in traditional treatments, while effective in deactivating microorganisms, can result in changes to the sensory qualities and nutritional attributes of powdered substances. These alterations may include the degradation of vitamins, flavor, volatile oils, and bioactive properties.

Highlights
- Trends in RF-assisted processes for pest control, microbial and enzyme inactivation were reviewed.
- Challenges and prospects for the development of RF technology were discussed.
- RF processing can be considered mature to achieve pest control, microbial and enzyme inactivation at industrial scale.
- Properly designed RF processes allow treated foods to maintain color, texture, and nutrients.

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Commercial pasteurization by conventional heating for liquid foods reduces microorganism counts and inactivates undesirable enzymes [6]. Through the mechanisms of conduction and convection, heat is transferred from the external environment to the interior of the food. However, the treatment requires long process times and can cause overheating [7]. Furthermore, fouling in the heat exchanger due to high temperature impacts to a reduction in food quality. Therefore, avoiding fouling in equipment that leads to overheating or insufficient heating is a disadvantage of pasteurization process.

For solid and semi-solid foods, conventional heat treatments based on exposure to hot air and humidity transmit insufficient thermal energy to reach the core of the product. Surface exposure of food to heat causes cracks in addition to ineffective treatment of the core, leading to degradation of product quality [8]. Particulate foods such as grains and seeds (oilseeds, cereals, and nuts) are heat treated using dry heat, hot water, or steam. However, the short period of time can be ineffective, damaging the vigor of the seeds. On the other hand, the long heating time reduces the sensory quality of the food [9]. Seeds treated by chemical methods, including fungicides such as methyl bromide and phosphine may contain residues of these reagents. Furthermore, the use of fungicides can lead to increased resistance of the pest or pathogen [10]. Additionally, gases originating from the chemical method damage electrical equipment and destroy the ozone layer when in contact with the atmosphere. In this sense, the search for food decontamination technologies that maintain nutritional quality and sensory properties has become the focus of research in recent decades. Furthermore, issues related to food safety have triggered several emerging technologies, such as pulsed electric field [11], ozone processing [12], cold plasma [13], pulsed light [14], high pressure processing [15], microwave heating [16], infrared heating [17], ohmic heating [18], and radio frequency (RF) heating [19].

RF technology involves dielectric and electromagnetic heating with longer wavelength, resulting in deeper penetration [20]. The coupling of electromagnetic waves in food generates heat [21]. The alternating electric field applied to the dielectric material causes friction between the molecules due to the movement of ions and rotation of polarized molecules [22]. This friction generates heat inside the product and avoids limitations on the heat transfer rate. In RF heating, ionic conduction predominates, with charged ions exerting more influence on heat generation than water molecules. In food processing, RF applications include defrosting [23], disinfestation [10, 24], pasteurization/sterilization [25], drying [26], enzyme inactivation [27], improving gelling properties in foods [28], and modification of the internal structure of starch [29]. Additionally, volumetric heating caused by RF can substantially reduce the heat spent during food blanching [30, 31]. Moisture content influences the material behavior under RF processing: cellular tissues with higher humidity absorb more energy compared to tissues with lower humidity. In this way, moisture leveling through RF heating promotes uniform drying [32].

Although some recent reviews have widely discussed the RF technology [33–36], to the authors' knowledge there are no reviews addressing trends in the last five years on the RF applications in the food industry for pest control, microbial and enzymatic inactivation of solid, liquid, and powdered foods. In this context, the aim of this review is to outline the foundational aspects of RF technology and its evolving applications in food decontamination, addressing its advantages and disadvantages, along with the challenges and prospects for expanding the technology.

Fundamentals of Radio Frequency Technology

The application of RF is a widely disseminated technology in the telecommunications area. Its use in the heating field began at the end of the 19th century. Exploration in the food processing sector for blanching, dehydrating, defrosting, and cooking began in the mid-20th century [25]. In the 1960s, industrial production lines for defrosting vegetables and meat products began to spread RF technology [37]. Advancements in thermal processing studies are increasingly apparent due to the progress in computational technology and the enhancement of dielectric performance and temperature sensors, all contributing to the evolution of RF applications.

RF is defined as a non-ionizing wave that acts at specific frequencies of 13.56, 27.12, and 40.68 MHz with a wavelength of 22.1, 11.1, and 7.4 m respectively. Industrial, scientific, and medical use requires specific frequencies. The Federal Communications Commission has permitted the use of radio frequencies for heating at 13.56, 27.12 and 40.68 MHz to prevent RF interference in other areas, such as cellular telecommunications [7]. The thermal and electrical properties of a material placed in contact with an alternating electric field change due to this interaction [38]. The positive ions will move close to the negative pole of the electromagnetic field and vice versa, resulting in the phenomenon of ionic migration or conduction as illustrated in Fig. 1a. Furthermore, the effects of friction will generate heat in the dipole molecules that are rotating. These inverted movements occur thousands of times per second during the oscillation of the magnetic field. The collision of ions inside the material and the friction between the dipole molecules reflect on RF heating, as shown in Fig. 1b, c.

Figure 2 displays a schematic representation of an RF emitting equipment. The electromagnetic waves have the ability to penetrate dielectric materials and induce heating throughout space, through polarization processes ionic or dipole rotation [10, 39]. Compared to microwaves, radio waves have greater penetration depth due to their long wavelength. RF heating is generated by a standard oscillatory circuit and an automatic impedance matching system

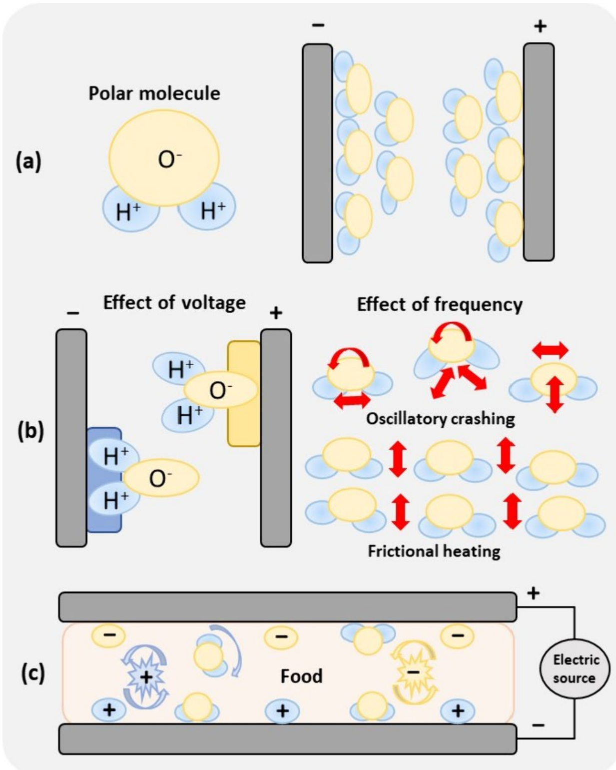


Fig. 1 Radio frequency heating mechanism. **a** Alignment of the polar molecule against the electrons, **b** Effect of voltage, oscillatory shock and frictional heating, **c** The collision of ions causing dielectric heating of the material (food)

can assist in maintaining the circuit impedance [9]. Consequently, coupling power stability can be maintained during warm-up while maintaining a fixed frequency and controlling feedback. It is important to highlight that the moisture content of the material is the factor that most influences the dielectric properties [40]. Likewise, it contributes to improving heating uniformity during the RF process.

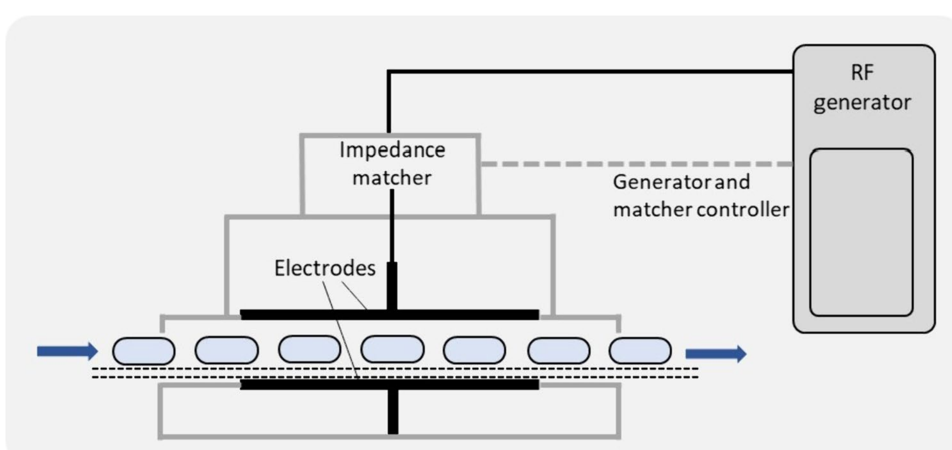
The dielectric properties of materials describe their interaction with an alternating electric field and quantify their ability to reflect, store, and transmit electromagnetic energy. They are expressed as the complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$. The real component, ε', corresponds to the dielectric constant, representing the energy storage capacity of the electric field by the material. The imaginary component, ε'', represents the dielectric loss factor, which is related to the dissipation of electric field energy in the form of heat [41]. The penetration depth comprises the distance from the surface of a dielectric material, at which the incident power is reduced to 1/e ($e \approx 2.718$) of the original power, while electromagnetic waves propagate through this dielectric material [25]. Equation (1) describes the depth of penetration.

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

where d_p - depth of penetration (m), c - Speed of light in vacuum (3×10^8 m s^{-1}), and f - Frequency (Hz).

A signal analyzer connected to a sample holder by a probe provides the real and imaginary impedance values from which the dielectric properties of the material are computed [42]. When measuring dielectric properties using LCR [(Inductance (L), Capacitance (C), Resistance (R)] meters and impedance analyzers, a small voltage is applied to the ends of the target sample, which allows detection of the current passing through the food [43]. For values in the range 1–300 MHz, an LCR meter (5 Hz–3 GHz) [44] or impedance analyzer (20 Hz–3 GHz) [45] can provide accurate results. Spectrum/lattice/vector analyzers determine dielectric properties for high frequencies, in the range 30 kHz–8.5 GHz [46]. However, there is lower accuracy for products with low moisture content. These analyzers record the phase and amplitude of a reflected wave signal coming from a sample of material. The attenuation and

Fig. 2 Typical radio frequency heating system



phase change of the signal are measured and interpreted to obtain the dielectric properties of the material [47–49]. Dielectric properties can be determined by transmission and resonance. Transmission using an open coaxial probe sweeps microwave frequency. However, the technique lacks precision in measuring low loss factors [50]. The technique involves immersing the probe in a liquid or in contact with the flat face of the solid material (or powder). The measurement of the reflected signal is related to complex permittivity. A typical measurement system involves a vector network analyzer, a coaxial probe, and permittivity determination software. On the other hand, the resonance technique presents greater precision in determining dielectric properties and dielectric loss [51, 52]. Resonance can be promoted by the metal walls of a cavity or achieved by the dielectric sample. A dielectric sample inside a cavity disturbs its electromagnetic field, changing the resonance frequency and quality factor. The advantages of the technique involve easy preparation, measurement, and calculation of dielectric properties [50]. As disadvantages, the reproducibility of the test may be compromised due to the small size of the sample in relation to the cavity, as well as each frequency evaluated requires a different cavity [53].

Applications in Food Processing

This section covers the application of the RF technology to control pest in food grains, reduce microbial populations in liquids and powders, and inactivate enzymes in solid, liquid, and powdered foods, although RF energy also has other applications such as cooking [54], thawing [55], drying [56], roasting [57], and pre-treatment for vegetable oil extraction [58].

Pest Control

Pest cause post-harvest losses of up to 20% in oilseeds worldwide [59]. In this sense, RF heating is an alternative to chemical fumigations, helping to control pest in food grains [60]. Furthermore, environmental concerns, the organic food market and pest resistance to chemicals have pressured the industry to develop non-chemical treatments to promote disinfestation. Additionally, synthetic chemicals carry risks to human health through product contamination.

Table 1 presents studies of food grain disinfections by RF heating. Appugol et al. [59] reported the effect of RF on peanut quality and peanut oil to promote complete mortality of

Table 1 Food grain disinfections by RF heating

Commodities	Target pest	Processing temperature / holding time for 100% mortality of pest	Sample mass (kg)	Power (kW); Frequency (MHz)	Mode	Reference
Peanuts and peanuts oil	*Caryedon serratus*	Adults and eggs – 89.96 ± 1.05 °C – 8 min	N/A	10; 40.68	Continuous	[59]
Semolina	*Tribolium castaneum* (Herbst)	All life stages – 64.40 ± 1.40 °C – 8 min	N/A	10; 40.68	Continuous	[61]
Black beans (*Phaseolus vulgaris* L.)	*Acanthoscelides obtectus* (Say.)	N/A, 50 °C – 1 min	10 and 20	12; 27.12	Batch	[62]
Coix seeds	*Rhyzopertha dominica*	Adults – 50, 53, 56, and 59 °C and holding for 56.9, 22.8, 7.7, and 0.0 min	1	6; 27.12	Batch	[63]
Rough, brown, and milled rice	*Rhyzopertha dominica*	Adults – 54 °C – 11 min	6 and 2	15; 27.12	Continuous	[64]
Turmeric	*Lasioderma serricorne*	Eggs – N/A, 5.34 min Larvae – N/A, 4.77 min Pupae – N/A, 5.91 min Adult – N/A, 6.06 min	N/A	10; 40.68	Continuous	[65]
Wheat flour	*Tribolium castaneum* (Herbst)	All life stages – 74.6 ± 0.74 °C – 15 min	3	10; 40.68	Continuous	[66]
Mung beans	*Rhyzopertha dominica*	Adults – 54 °C – 6 min	6	6; 27.12	Batch	[67]
Mung beans	*Rhyzopertha dominica*	Adults – 54 °C – 6 min	6	6; 27.12	Batch	[68]
Milled rice	Rice moth (*Corcyra cephalonica*)	Eggs – 70 °C – 420 s Larvae – 56.9 °C – 300 s Adult – 45.8 °C – 180 s	0.2	3; 27.12	Batch	[69]

Caryedon serratus. Treatment at 89.96 °C reduced the moisture content from 7.45 to 2.11% and the protein content from 22.17 to 20.94% without changing the color of the product. Furthermore, the oil extraction yield increased by 18.97% after treatment, with improved composition through the reduction of saturated fatty acids and an increase in unsaturated fatty acids. Similarly, Indumathi et al. [61] evaluated the disinfestation of *Tribolium castaneum* (Herbst) semolina using 40.68 MHz, 10 kW RF heating. Treatment with 8 min of exposure was sufficient to disinfest 100% of *T. castaneum* in semolina, achieving 100% mortality at 64.4 °C. To the authors, RF technology is a promising and ecological technology for promoting grain disinfestation.

Weevil mortality at 50 °C was investigated using pilot-scale RF at 12 kW and 27.12 MHz [62]. The 10 kg batch was heated in 2.72 min, while the 20 kg batch only took 1.29 min to reach 50 °C, demonstrating rapid heating volumetric. Uniform indices close to zero were obtained for both batches. Similarly Hou et al. [63] reported RF technology as a post-harvest physical insecticide for eliminating *Rhyzopertha dominica* insects in coix seeds. The authors studied different temperatures and times of the sample kept in ambient air inside the RF cavity. Energy efficiency occurred by heating the sample 50 °C by RF, keeping it 56.9 min in ambient air. Aiming for a short time process, just heating to 59 °C was sufficient without exposure to ambient air. The RF commercial system has been effective in eliminating *R. dominica* from rice. Hou et al. [64] reported that heating at 54 °C for 11 min was enough for pest mortality. The process yield was 594.8 kg h^{-1} with an electrical cost of US$ 2.53 per ton. Thus, these positive findings highlight RF as a non-chemical pest disinfectant in post-harvest grains.

Microbial Inactivation

Microbial decontamination by RF heating is based on the diffusion of heat at a faster rate within the cell of the microorganism compared to other means. The cells are thermally destroyed with a low heating rate [70]. The mode of RF heat transfer is radiation. In this way, microbial DNA and essential proteins absorb this energy, physically modifying the cellular structure and function of the microorganism [2]. The effect of RF heat treatment to reduce microbial population depends on the species, cell wall structure, RF frequency, and heating uniformity.

Table 2 shows the population reduction of microorganisms for various foods using RF technology. Liu et al. [71] studied low-temperature, long-term RF pasteurization of onion powder to evaluate the inactivation of *Salmonella enterica*. RF heating reached 66 °C in 180 s. After 38 h of treatment, there was a reduction in the microbial population of 3.4 log. Furthermore, the quality of the onion powder was not changed after the process. Although *Salmonella* is the indicator microorganism validating thermal pasteurization, several studies have reported *Enterococcus faecium* as a suitable substitute for pasteurizing spices and herbs [72–74]. In this sense, Wason et al. [75] evaluated RF pasteurization in packaging containing dried basil leaves for inactivation of *Salmonella enterica* and *E. faecium*. The *Salmonella* population was reduced by 4.58 ± 0.14 log, while *E. faecium* by 2.59 ± 0.46 log using RF treatment for 105 s vertically. After the process, the quality analysis demonstrated that there was no change in the color, total phenolic content and antioxidants of the product. In this context, RF pasteurization of a packaged product together with steam ventilation eliminates cross-contamination, improves heating uniformity, avoiding impacts on product quality.

Jeong et al. [76] reported the effect of rice milling degree on RF heating rate, inactivation of *Salmonella Typhimurium* and *Staphylococcus aureus* and change in color. Samples were heated from 0 to 75 s. The highest heating rate was observed for the 2% grinding grade. High values of pathogen reduction with the same degree of grinding and 75 s of treatment resulted in logarithmic reductions of > 6.09 and > 7.90 for *Salmonella Typhimurium* and *Staphylococcus aureus*, respectively. The color of the samples was not deteriorated by RF heating, regardless of the degree of grinding, with no significant effect. In another study, RF technology was evaluated in the pasteurization of egg white powder in continuous mode [77]. Thermal processing for 2 h at 80 °C showed a logarithmic reduction of > 6.69 for *Salmonella* and > 6.78 for *E. faecium*. The greater resistance and similar kinetics to *Salmonella* make *E. faecium* a potential surrogate microorganism for pathogen evaluation. For the authors, the validated thermal process can be expanded to the egg industry. Furthermore, the continuous process could process a larger quantity of products in a shorter time compared to stationary RF heating. Hot air, intermittent stirring, or electrode modifications can help improve the uniformity of continuous heating [92, 93].

Enzyme Inactivation

Enzymes are like biocatalysts that act in reactions in the metabolism and physiology of plants. However, their activities after harvest lead to food deterioration, through color change, generation of odors and nutritional loss [94]. In food grains, the most relevant enzyme is related to color change and the development of strange flavors due to contact with substrates such as lipids, polyphenols, and proteins [95]. Compared to disinfestation and pasteurization treatments, RF heating is rarely reported for enzyme inactivation.

Table 3 displays studies on enzyme inactivation by RF and their main findings. In general, studies compare RF with conventional hot water blanching and evaluate enzyme inactivation, texture, weight, vitamin C content, and electrolyte

Table 2 RF heating treatment of food and their reductions in microorganisms

Commodities	Target microorganism	Population reduction (log), moisture content (w.b.), water activity (a_w)	Processing temperature, time	Sample mass (g)	Power (kW); Frequency (MHz)	Mode	Reference
Onion powder	*Salmonella enterica* Enteritidis PT 30	3.4 log 7.4 ± 0.1% w.b. a_w – 0.32 ± 0.01	66 °C, 210 s	N/A	8; 27.12	Batch	[71]
Cumin seeds	*Salmonella enterica* and *Enterococcus faecium*	> 6.1 ± 0.2 log – *S. enterica* > 6.8 ± 0.1 log – *E. faecium* 10.19 ± 0.01% (w.b.) a_w – 0.65 (after inoculation)	93.05 ± 0.21 °C, 90 s	20	6; 27.12	Batch	[72]
Dried basil leaves	*Salmonella* and *E. faecium*	4.58 ± 0.14 log 2.59 ± 0.46 log 10.9 ± 0.25% w.b. a_w – 0.620 ± 0.003	100 °C, 105 s	N/A	1; N/A	Batch	[75]
Rice (*Oryza sativa* L.)	*Salmonella enterica* Serovar Typhimurium and *Staphylococcus aureus*	6.31 ± 0.7 log 7.80 ± 0.7 log	90 °C, 75 s	25	N/A; 27.12	Batch	[76]
Egg white powder	*Salmonella* and *E. faecium*	> 6 log for both microorganism 7.11 ± 0.11% w.b. a_w – 0.31 ± 0.01	55 min + 2 h hot hair	550	6; 27.12	Continuous	[77]
Roasted grain powder	*Escherichia coli*, *Salmonella* Typhimurium, and *Bacillus cereus*	4.68 log 3.89 log 4.54 log	120 °C, 120 s (time to reach the temperature)	25	N/A; 27.12	Batch	[78]
Nitrite-free sausages	*Bacillus subtilis*	7 log	RF – 125 °C, 2 min + retort heating – 121 °C, 7 min	840	8; 27	Batch	[79]
Shell egg	*Salmonella* Typhimurium	> 5 log	30 W – 30 °C, 8 min 35 W – 30 °C, 6 min 30 W – 34 °C, 7 min 35 W – 34 °C, 5.5 min 35 W – 38 °C, 4.5 min	59–61	2; 40.68	Batch	[80]
Shell egg	*Salmonella* Typhimurium	5 log for RF + Hot water immersion (HWI) or Hot water spraying (HWS)	RF – 38 °C, 4.5 min RF/HWI – 56.7 °C, 19.5 min RF/HWS – 56.7 °C, 24.5 min	59–61	N/A	Batch	[81]
Shell egg	*Salmonella* Typhimurium	6.31 ± 0.7 log	RF – 34 °C, 6 min HWI – 56.7 °C, 20 min	59–61	1; 60	Batch	[82]
Cranberry juice	*Escherichia coli*	6.57 log	40 °C, from 540 to 3240 µs	N/A	N/A	Continuous	[83]
Ground black pepper	*Salmonella* spp. and *Enterococcus faecium*	> 5.98 log – *S.* spp > 3.89 log – *E. faecium* 12.8 ± 0.1% (w.b.) a_w – 0.664 ± 0.003	78.1 and 80.1 °C, 120 and 130 s respectively.	400	6; 27.12	Batch	[84]
Barley grass powder	*Escherichia coli*	3.8 ± 0.17 log 0.09 ± 0.001% (w.b.)	RF – 4 °C min^{-1} until 80 °C + Hot air (80 °C – 10 min)	1500	6; 27.12	Continuous	[85]

Table 2 (continued)

Commodities	Target microorganism	Population reduction (log), moisture content (w.b.), water activity (a_w)	Processing temperature, time	Sample mass (g)	Power (kW); Frequency (MHz)	Mode	Reference
Wheat flour	*Enterococcus faecium* NRRL B-2354	2.5–3.7 log $a_w - 0.45 \pm 0.02$	80–85 °C	1800	6; 27.12	Batch	[86]
Wheat flour	*Salmonella* Enteritidis PT 30 and *Enterococcus faecium*	$D_{85°C}$ was calculated to be 18 min to achieve 1 log reductions 8.34 ± 0.12% (w.b.) $a_w - 0.45 \pm 0.02$	Heated up to 85 °C, switched off and held for up to 39 min	3000	6; 27.12	Batch	[87]
Spide paprika	Mesophilic aerobic bacterial	2.6×10^6 log (95 °C) 3.3×10^6 log (105 °C) 3.5×10^6 log (115 °C) 20.3% (w.b.)	95, 105, 115 °C, 50–90 s.	N/A	10; 13.5	Batch	[88]
Red pepper	*Salmonella typhimurium*	> 5 log 6.8% (w.b.) a_w – 0.57, 0.64, 0.71, 0.74	50 to 90 °C, 0 to 180 s.	N/A	12; 27.12	Batch	[89]
Buckwheat kernels	*Bacillus cereus*	> 2.0 log 12.8% (w.b.) $a_w - 0.75$	85, 90, 95, 100 and 105 °C, 0, 5, 10, 20, and 30 min	1000	6; 27.12	Batch	[90]
Shredded in-shell walnut	*Staphylococcus aureus*	> 4 log 8.50 ± 0.03% (w.b.) (whole sample)	5 °C min^{-1}, 70 °C	2080 and 1850	6; 27.12	Batch	[91]

leakage. Yao et al. [96] observed a drop from 66.03 to 6.46% in the activity of the peroxidase enzyme by increasing the RF heating temperature from 65 to 85 °C in the treatment of lettuce stems. In another study, Yao et al. [97] combined steam-assisted RF blanching for application to lettuce cuboids. RF treatment at 80 °C followed by steam application for 1 min demonstrated excellent heating uniformity and sample quality, with a 95% reduction in peroxidase activity and retention of almost 80% of vitamin C.

Sun et al. [99] reported the effects of RF blanching and boiling water on the inactivation of the lipoxygenase enzyme, nutritional content, and grain morphology of sweet corn. RF heating from 50 to 80 °C reduced enzyme activity to 4.68%. Physicochemical properties such as color, texture, and nutrient content were better preserved compared to blanching in boiling water. According to the micrographs in Fig. 3, the increase in temperature during RF bleaching damaged the cells. On the other hand, hot water bleaching damaged cells more severely. Disruption of the cell wall exposed the cystic surfaces of the cells. This phenomenon is known as pectin depolymerization, responsible for the deterioration of the texture of foods and the softening of plant tissue during heat treatment [106, 107]. Yarrakula et al. [100] investigated lipase inactivation from pearl millet (*Pennisetum glaucum* L.) grains by combining hot air-assisted RF technology. Lipase activity was reduced to 2.7% with the sample 15% hydrated and processed for 15 min using a heating rate of 5.2 °C min^{-1}. A longer period of exposure to the treatment as well as greater sample humidity improved the bonding properties. For the authors, the study adds value and promotes the use of underused gluten-free cereals due to rapid rancidity. Furthermore, pearl millet grains present nutritional and therapeutic benefits.

Advantages and Disadvantages of Radio Frequency Technology

The use of RF has several distinct characteristics in contrast to conventional heat transfer and diffusion methods. To prevent Ohmic heating, it is crucial to ensure that the electrodes do not make direct contact with the food when employing RF heating units. This technology is suitable for both liquid and solid food products, and its wavelength exceeds that of microwave frequencies. Due to their greater power capacity, RF waves penetrate deeper into the material compared to conventional microwaves. Thus, heat is internally generated within the material, leading to a more even distribution. Furthermore, the construction of large-scale RF units is more convenient and contributes to improving the quality of the final product. Other notable advantages of this sustainable technology include increased energy efficiency, moisture leveling, contactless heating, and faster drying and curing times [108]. The operating and equipment costs compared to conventional heating systems are the disadvantages of the technology. The total costs of implementing RF technology can vary between 2500 and 6000 euros per installed kilowatt of RF power. The capital costs involved can be divided into: (1) energy generator – 20–30%; (2) applicator – >35%; (3) power transmission – 5–10%; (4) auxiliary instrumentation – 5–30%; (5) installation and startup – 5–15% [109]. However, considering that the cost per installed kilowatt of RF power decreases when the nominal plant power exceeds 12 kW, and considering that electricity to run a RF power can come from renewable sources at a competitive price, and taking into account the minimization of handling, RF technology is an attractive choice.

Challenges and Future Perspectives

Despite being in the market for an extended period, the adoption of the RF technology within the industry has progressed at a relatively modest pace. The design of RF heating systems is made complex by the requirement for comprehensive data on the dielectric properties of food products, as well as the dimensions, configurations, and placements of RF electrodes to achieve uniform temperature distribution [70]. Furthermore, the high intensity of the electric field in the sample causes a dielectric breakdown, causing destruction of the product or rupture of the packaging [110]. Moist foods with high salt content may exhibit non-uniform heating at the RF frequency, leading to product loss [111]. Controlled food thawing is difficult to achieve without other heat exchange mechanism able to mitigate possible run away heating zones [23]. Additionally, there are still some challenges such as analysis in real time, lack of data for comparison, high cost due to electricity, and difficulty in measuring temperature without contact in order to avoid interaction with the electromagnetic field [112].

A future of RF technology in the food industry cannot be imagined without the implementation of key-enabling technologies in this sector. Future research should focus on introducing in industrial applications the use of digital technology, computer simulation, and parameter evaluation. As variations in temperature, humidity, and electric field intensity inside materials are complex during RF drying, the use of online digital solutions for monitoring, and measurement is recommended. Computer simulation allows a quick and low-cost analysis, without environmental limitations. It helps in simulating and optimizing parameters to improve heating uniformity, often eliminating the need for a series of experiments [113].

Table 3 RF heating treatment of food for enzyme inactivation

Commodities	Target enzyme	Relative residual enzyme activity/, moisture content (w.b.), water activity (a_w)	Processing temperature + time	Sample mass (g)	Power (kW); Frequency (MHz)	Mode	Main findings	Ref.
Wheat germ	Lipase	23%/11.33 ± 0.20% w.b., a_w – 0.632	100 °C, 15 min	650	6; 27.12	Batch	RF treatment at 100 °C with retention in hot air for 15 min led to a reduction in lipase activity by 18.2%, while treatment at 110 °C and retention for 5 min exhibited a reduction of 22.5% of its initial value. Furthermore, RF stabilization improved the color and water/oil absorption capacity of wheat germ.	[27]
Stem lettuce	Peroxidase	6.46%/Unknown	85 °C	N/A	6; 27.12	Batch	Increasing the temperature from 65 to 85% led to a reduction in peroxidase activity from 66.03 to 6.46%. Likewise, there was a change in weight loss, texture, electrolyte leakage, color, and decrease in vitamin C. RF treatment at 75 °C showed less cellular damage and greater nutrient retention compared to hot water bleaching at 95 °C – 2 min.	[96]

Table 3 (continued)

Commodities	Target enzyme	Relative residual enzyme activity/, moisture content (w.b.), water activity (a_w)	Processing temperature + time	Sample mass (g)	Power (kW); Frequency (MHz)	Mode	Main findings	Ref.
Stem lettuce cuboids	Peroxidase	1.30%/ Unknown	> 90 °C, 660 s	N/A	6; 27.12	Batch	Steam-assisted RF bleaching prevented local overheating, promoting uniform temperature distribution. Furthermore, there was less thermal damage to the cells, maintaining color and texture and greater retention of vitamin C.	[97]
Salmorejo (tomato, olive oil, and breadcrumbs)	Pectin methylesterase, peroxidase, and polyphenol oxidase	0%, < 10%, > 30%/ Unknown	80 °C, 9.8 s	N/A	N/A; 27.12	Batch	Conventional heating and RF treatments significantly reduced mesophilic and sporulating microorganisms in addition to inhibiting pectin methylesterase and peroxidase and, to a lesser extent, polyphenol oxidase. However, the treatments did not inhibit the polygalacturonase enzyme. The temperature of 80 °C balanced thermal damage to the product and inhibited microorganisms and enzymes. Above this value, the product becomes overheated.	[98]

Table 3 (continued)

Commodities	Target enzyme	Relative residual enzyme activity/, moisture content (w.b.), water activity (a_w)	Processing temperature + time	Sample mass (g)	Power (kW); Frequency (MHz)	Mode	Main findings	Ref.
Sweet corn (*Zea mays* L.)	Lipoxygenase	4.68%/Unknown	80 °C	80, 120, and 160	6; 27.12	Batch	RF bleaching led to better texture, color, and nutrient content compared to samples treated by boiling water. Increasing the temperature from 50 to 80 °C in RF treatment decreased the enzymatic activity to 4.68%.	[99]
Pearl millet	Lipase	2.70%/15% (w.b)	80 °C, 15 min	N/A	10; 40.68	Continuous	The synergistic effect of hot air-assisted RF treatment showed a maximum lipase inactivation of 97.30% in a sample with 15% hydration level processed for 15 min. Increasing the exposure time to the treatment improved the bonding properties. The physical and functional properties of the treated millet reached acceptable levels for flour.	[100]
Green peas (*Pisum sativum* L.)	Lipoxygenase and peroxidase	0.90 ± 0.78% - Lipoxygenase 1.10 ± 0.71% - Peroxidase / Unknown	85 °C, 110 s	80	6; 27.12	Batch	Increasing the temperature from 60 to 85 °C significantly altered the weight, color, electrolyte leakage, and texture of the peas, leading to aggravated degrees of change.	[101]

Table 3 (continued)

Commodities	Target enzyme	Relative residual enzyme activity/, moisture content (w.b.), water activity (a_w)	Processing temperature + time	Sample mass (g)	Power (kW); Frequency (MHz)	Mode	Main findings	Ref.
Stem lettuce	Peroxidase	< 5% - Peroxidase / Unknown	85 °C, 5 min	N/A	6; 27.12	Batch	Peroxidase reduced to < 5% by RF showed better physicochemical properties and less cellular damage compared to hot water bleaching. Furthermore, increasing the electrode gap and changing the sample height improved the uniformity of RF heating.	[102]
Soybean	Lipoxygenase	5.7%/15% w.b	110 °C, 210 s	37	1.8; 27.12	Batch	The soy protein isolate presented better functional properties compared to the isolate obtained by conventional heat treatment. The analysis of volatile compounds in soy milk indicated a decrease in the concentration of hexanal from 521 to 116 μg L^{-1} and that of 1-hexanol, from 271 to 6.99 μg L^{-1}, demonstrating an improvement in the sensorial properties using RF treatment.	[103]

Table 3 (continued)

Commodities	Target enzyme	Relative residual enzyme activity/, moisture content (w.b.), water activity (a_w)	Processing temperature + time	Sample mass (g)	Power (kW); Frequency (MHz)	Mode	Main findings	Ref.
Sweet potato	Peroxidase	< 10%/64.89 ± 2.23 w.b	90 °C + hot water bath (90 °C) for 2, 4, and 6 min	N/A	6; 27.12	Batch	RF combined with hot water bleaching achieved a peroxidase enzyme inactivation level < 10% and provided better color and texture values compared to hot water bleaching. Furthermore, optimal RF heating uniformity occurred with electrode gap of 90 mm and sweet potato thickness of 60 mm.	[104]
Rice bran	Lipase	19.2%/11.16% w.b., a_w – 0.671	100 °C, 15 min	200	6; 27.12	Batch	RF treatment followed by heated air did not significantly change the quality of rice bran. Furthermore, its storage was improved with the treatment. The oil extracted from treated rice bran indicated free fatty acid and peroxide content values below acceptable limits.	[105]

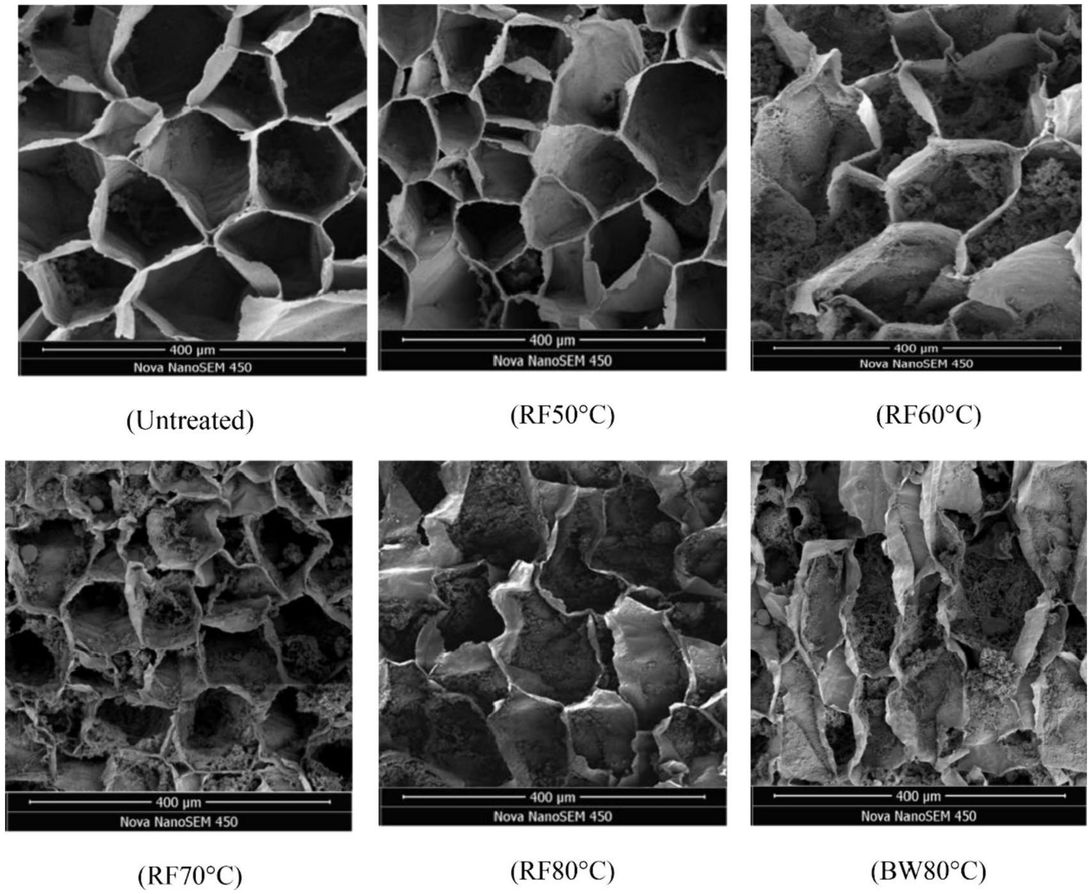


Fig. 3 Micrographs of untreated and treated sweet corn by RF and boiling-water (BW). Adapted from Sun et al. [99], with permission from Elsevier

Among the commercially accessible software for heat transfer and/or electromagnetic field displacement, many are based on finite element method, such as COMSOL Multiphysics [114] (an update of an early version called FEMLAB, which was used to develop and solve the first model of RF heating of food [115]), High-Frequency Structure Simulator (HFSS-ANSYS) [116], Quickwave 3D (QW3D) [117], and TLM-FOOD HEATING [118]. COMSOL Multiphysics software allows coupling different physical phenomena and it has been used to simulate RF heating behaviors through the concurrent solution of electromagnetic and heat transfer equations [119]. Model parameters such as top electrode voltage, thermal conductivity, heat transfer coefficients, and dielectric properties are entered before simulation. For each simulation, the model geometry is based on the sample and the RF heating unit. After solving the simulation, the average temperature and heating uniformity index are determined considering the volume, surface, and target point. Subsequently, validating the simulation model and its solution involves heating the samples at predetermined locations within the RF unit. Thus, there is an understanding of the influence of the shape and size of granular particles on the uniformity of RF heating [120]. Additionally, the simulation helps in selecting the packaging shape [121]. Huang et al. [122] used COMSOL software to simulate RF heating of insects in soybeans in the upper, middle, and lower layers of the container. Experimental validation using Indian moth larvae indicated a differential heating of 5.9–6.6 °C more than the host soybean when RF treatment occurred from 25 to 50 °C, demonstrating that the heating rate for insects was 1.4 times higher than for soybeans. The orientation of the insect body in the cold point of the layers, combined with its size, influences the heating inside its body.

Regarding industrial application, the ultimate objective of the research groups is the dissemination of the technology on a large scale. Efforts should/could be spent to integrate RF processing systems in power grid supplied by renewable energy, eventually to design and place on the market integrated RF systems, to be mounted on vehicles and transported and used even in rural areas, where eventually fast and reliable inactivation method is needed to prevent spoilage of agricultural products, preventing their possible infestations before selling the products. However, there are gaps between fundamental and industrial-scale research. Equipment maintenance is still a bottleneck for the adoption of RF technology. Additionally, service and maintenance contracts for RF equipment are expensive. The electric arc is another barrier found in industrial processing. Arcing in RF treatment is very common and several methods/algorithms have been implemented in hardware to avoid this phenomenon. However, most of them end up shutting down the RF system after a certain number of arcing events are encountered. This division makes it difficult to verify the integrity of the process.

Most studies have focused on the aspect of RF heating uniformity and electrode placement, etc. However, the area of dynamic impedance matching has not received as much attention, demonstrating opportunities to improve the technology. Likewise, future research should seek to simplify the structural design of RF generation and the cavity, aiming to reduce costs on an industrial scale [123]. The energy consumption and economic costs of an industrial technology are crucial factors and are ignored in fundamental research. Furthermore, the variation in sample volume alters the uniformity of heating and subsequent drying. Therefore, laboratory or pilot scale tests must be validated according to protocols to promote application, for example in the food industry.

Conclusion

In recent decades, researchers have explored emerging RF technology as a potential substitute for traditional heat treatment. Furthermore, there has been extensive documentation of the dielectric properties of various products. The non-uniformity of the product can often be the main limitation of the treatment as it reduces the quality of the product and reduces food safety, favoring the development of microorganisms. In this context, this review addressed application trends over the last five years, considering RF heating as a promising alternative for the food industry. Studies are focused on simulations, equipment designs, and process optimization to overcome this obstacle. RF technology has been reported for liquid, solid, and powdered foods, as well as pre-packaged foods. The advantage of RF heating a packaged product is the reduced risk of cross-contamination. The physical state of food represents a particularity in studies due to different sizes and chemical composition. According to the objectives of the studies, RF proved to be a green technology for pest disinfestation, enzymatic and microorganisms inactivation, achieving food safety goals without changing the quality of the product. Additionally, it has the capacity to maintain nutritional, physicochemical, and sensory attributes due to shorter processing time. Published experimental results are mostly referred to 27.12 MHz: there is still room to explore the benefit of this technology at higher or lower frequency, considering the different penetration depths that can be achieved. Considering the complexity of an optimal design of such processes and equipment, the use of computer-aided food engineering methodology could definitely contribute to expand the use of RF-assisted processes for a more sustainable food industry.

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Declarations

Ethical Approval Not applicable.

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