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THE LATEST DEVELOPMENT OF RADIO-FREQUENCY APPLICATIONS IN THE FOOD INDUSTRY: ADVANTAGES AND DRAWBACKS

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Abstract

The quest for innovative processing solutions that meet both food safety and quality standards and sustainability goals (in terms of processing, preservation, and consumption) has led to a growing interest in technologies like radiofrequency (RF) technology. Although the mechanisms behind this technology have been thoroughly explained and are well-documented in the literature, and its advantages for industrial applications are recognized in several studies, the widespread adoption of RF technology for various agri-food products thermic treatment, remains limited due to unsolved issues. One of the main challenges in applying RF technology on a large scale is the need to adapt equipment and technology according to the specific characteristics of the product (e.g. raw material, finished product, liquid, semi-liquid, solid, packaged, unpackaged) and the intended purpose (e.g., processing, preservation, sanitization). This paper aims to review recent findings in this area, highlighting both the benefits and challenges of RF technology application for different food products thermal processing. Addressing these challenges requires continued scientific research in various directions within this field.

***Key words**: benefits and challenges, food processing, RF technology.*

INTRODUCTION

Radiofrequency (RF) technology is an emerging and effective approach for food processing. It operates on the principle of capacitive dielectric heating, enabling rapid and uniform heating, even in solid food products (Lu et al., 2007; Piyasena et al., 2003; Y. Zhao et al., 2000).

Radio frequency (RF) technology utilizes electromagnetic waves within the 3 kHz to 300 MHz range to generate heat in food products (Altemimi et al., 2019; Radhakrishnan, 2013; Sun et al., 2023; 2025; Zeng et al., 2022). It is extensively used in the food industry for applications such as drying, thawing, and pest control (Alfaifi et al., 2014; Farag et al., 2011; Gao et al., 2010; Jumah, 2005; Kocadağlı et al., 2012; Wang et al., 2014). Studies indicate that RF technology has potential for pasteurizing and sterilizing packaged foods (Cui et al., 2023; Lara et al., 2022). However, a major challenge with RF heating is the tendency for overheating at the edges and corners of food samples (Jiao et al., 2015). RF technology is also applied to the control of microorganisms, especially fungi that contaminate food products (Berni and Brutti, 2023).

In RF heating, a high-voltage alternating current (AC) is applied to parallel electrodes configured as a capacitor, generating electromagnetic waves at a frequency of 27.12 MHz - significantly higher than those used in ohmic and pulsed electric field (PEF) treatments (Costa & Marra, 2024; Dong et al., 2021; Li et al., 2024; Ozturk et al., 2020). Unlike microwave heating, where waves are dispersed by a magnetron within a cavity, RF heating directly immerses food between the electrodes. This capacitive nature, combined with the longer and more penetrating wavelengths of RF waves, ensures a more uniform heating process compared to microwave technology (Zhao et al., 2000).

Thermal processing is widely used for pasteurization and decontamination to improve food safety and extend shelf life. However, this method affects the physical and technological properties of food, primarily due to alterations in gluten structure and starch configuration. (Gelinas & McKinnon, 2004; Neill et al., 2012; Sun et al., 2014).

Researchers have extensively investigated RF heating for processing flours and powders. For instance, studies have examined RF heating's effects on wheat (Kim et al., 2004), corn (Ozturk et al., 2017), and potato flours (Zhu et al., 2021), as well as its use in pasteurizing wheat flour (Boreddy et al., 2019; Liu et al., 2018b). Other work has explored RF treatment of spice powders like red pepper (Choi et al., 2018; Jiao et al., 2019; Zhang et al., 2020), paprika and cumin (Ozturk et al., 2017), alongside applications in infant formula (Zhang Zhu et al., 2020) and egg white powder (Kar et al., 2020). More recently, the effects of superheated steam on wheat flour properties have also been studied (Ma et al., 2021).

RF heating offers several additional benefits, including improved energy efficiency through volumetric heating, which minimizes energy waste. Its compact design reduces the required production floor space, making it ideal for facilities with limited room. Furthermore, RF technology is highly compatible with automated production systems, supporting both batch and continuous flow processing, thereby enhancing operational efficiency and scalability (Manzocco et al., 2008).

RF HEATING APPLICATIONS IN BAKERY INDUSTRY

Zhang et al. (2025) demonstrated that strategically positioning RF wave transmission holes along the metal susceptor's long sides, particularly near colder areas, significantly improved heating uniformity, speed, and energy efficiency. The researchers found that the energy transmission area was crucial for overall efficiency. Simulations confirmed that the ideal hole diameter increased with the sample's length-width ratio and height, but exceeding a certain size reduced electric field concentration. Optimized susceptor designs boosted energy efficiency by approximately 10%, with specific configurations reaching 15% and 18% improvements for different susceptor sizes. Furthermore, the study established a precise relationship between sample dimensions and optimal hole diameter, with minimal error. These results provide vital guidance for enhancing RF heating efficiency in metallized food packaging for industrial applications. Radio frequency (RF) heating presents a promising approach for food preservation and extending the shelf life of food products.

In their study, Mitelut et al. (2015) inoculated rye bread with three food spoilage fungi - *Aspergillus flavus*, *Penicillium expansum*, and *Fusarium graminearum* - before undergoing RF technology at varying temperatures (60°C, 80°C, and 100°C) to evaluate its effectiveness in inhibiting fungal growth. The results indicated that RF technology successfully inhibited fungal development on the surface of rye bread, demonstrating its potential as an effective method for controlling bread spoilage fungi.

RF drying is widely used after baking in the production of cookies, crackers, cereals, and snacks (McHugh, 2016). Traditional drying methods often create moisture gradients within these foods, leading to surface cracks. RF drying addresses this issue by delivering energy uniformly, reducing moisture differences and preventing cracks. Additionally, this method prevents flavour degradation and discoloration caused by excessive heat buildup.

RF drying also enhances production efficiency by increasing conveyor speed, stabilizing moisture levels, lowering drying temperatures, and minimizing surface marks from processing equipment (Palamthodi et al., 2021). Research by Anese et al. (2008) examined the impact of RF heating on acrylamide formation in baked goods. Their findings indicated that incorporating RF heating in the final baking stages, particularly when residual moisture levels were still high (around 10%), helped maintain low acrylamide levels. This suggests that combining conventional hot air baking with RF heating can be an effective approach to improving both product quality and food safety (Costa & Marra, 2024).

RF HEATING APPLICATIONS IN MEAT AND FISH INDUSTRY

To minimize quality degradation and flavour loss associated with autoclaving, a pickering emulsion (ZS) was formulated using zinc oxide nanoparticles (ZnO NPs) loaded with star anise essential oil (SAEO) to treat cooked tiger skin chicken feet. This emulsion was then combined with radiofrequency (RF) technology for pasteurization, ensuring enhanced preservation of quality and sensory attributes. The experimental results conducted by indicate that ZSRF pasteurization effectively keeps microbial levels in chicken foot samples low, outperforming the combined treatment of ZnO and RF. Compared to conventional high-pressure sterilization (HPS), this combined pasteurization approach minimizes flavour loss and the development of undesirable flavours while also regulating colour changes and preventing lipid and protein oxidation (Wei et al., 2025).

The dielectric properties of lean beef were analysed across different frequencies and temperatures, ranging from frozen to unfrozen states, to better understand its behaviour during RF heating (Bedane et al., 2017). Researchers conducted experiments to thaw lean beef using radio frequency (RF) energy, testing both stationary and continuous processes. In stationary setups, the distance between electrodes affected how evenly the meat heated. In continuous thawing using a conveyor belt, both electrode spacing and belt speed were critical factors. Notably, the moving conveyor system resulted in slightly more uniform heating. The data from these experiments can be used to develop models and simulations that optimize RF thawing parameters (Bedane et al., 2017).

Beef sausage heated using superheated water (SW)-assisted RF technology exhibited enhanced quality attributes, such as improved texture, colour, and microstructure, compared to those heated with SW alone. These enhancements were due to the shorter heating duration and more uniform temperature distribution achieved with RF technology. Consequently, this research suggests that SW-assisted RF technology could be a rapid and efficient method for safely and effectively heating various food products (Wang et al., 2024).

Cao et al. (2021) investigated using a combination of hot air and radio frequency heating (RF-HA) to dry tilapia fillets. Their aim was to achieve faster, more even drying and improve the fillet's quality. They tested different fillet thicknesses and examined the impact of wrapping the fillets with skin or gauze.

The results showed that RF-HA drying significantly speed up the drying process compared to just hot air, with drying rates increasing by 1.1 to 1.4 times. Fillets dried with RF-HA rehydrated better and shrank less, especially the thicker ones.

RF HEATING APPLICATIONS IN MILK PROCESSING INDUSTRY

The superior thermal efficiency and enhanced heating uniformity of radio frequency (RF) and microwave processes have been shown to effectively achieve comparable or improved bacterial and enzymatic inactivation in liquid and semi-solid foods. Additionally, these methods help preserve the sensory and nutritional quality of fresh products more effectively than conventional pasteurization (Abea et al., 2023).

In their study, Tonti et al. (2024) explored the influence of two intrinsic food factors namely fat content and matrix structure, on the RF inactivation of *S. typhimurium* and *L. monocytogenes* in dairy model systems. Regarding fat content, the effect on microbial inactivation varied depending on the system type and microorganisms. However, there was a general trend where increased fat content (5.9%) led to higher inactivation (greater "k" values, where "k" is defined as inactivation rate constant according to Arrhenius relation) at elevated temperatures (above 70°C). This phenomenon was attributed to the faster dielectric heating of fat compared to water, potentially exposing microorganisms to higher temperatures at the microscale when fat content is higher. For matrix structure, the k value was typically higher in gel matrices than in liquid matrices, which is contrary to the behaviour observed with conventional heating. This effect was believed to be linked to the direct heating of microorganisms by RF and the slower dissipation of heat in gel matrices (Zhang H. et al., 2025).

RF HEATING APPLICATIONS IN THE FRUIT AND VEGETABLE PROCESSING INDUSTRY

Pang et al. (2024) studied the impact of RF heating on polyphenol oxidase (PPO) activity by applying four kinetic models, with the Logistic and Bi-phasic models demonstrating the best fit. The study revealed that RF heating modified the secondary and tertiary structure of mushroom PPO, decreasing α-helix content while increasing surface hydrophobicity. Spectral analysis across different RF heating temperatures and durations showed that both factors influenced PPO inactivation. A redshift in maximum fluorescence intensity was observed as heating time and temperature increased, indicating structural disruption, exposure of hydrophobic groups, and enhanced surface hydrophobicity. These structural alterations were directly correlated with changes in PPO activity. Additionally, colour test results demonstrated that RF heating effectively inhibited mushroom browning. By correlating enzyme activity with structural modifications and establishing a kinetic model for PPO inactivation, this study provides a theoretical foundation for future applications in food processing.

The research conducted by Ranjan et al. (2024) highlight the effectiveness of radiofrequency cold plasma (RF-CP) treatment in significantly reducing microbiological contamination in cashew nuts while preserving their sensory and nutritional properties. The study revealed that a plasma mixture of N_2 (70%) and O_2 (30%) was more effective in microbial decontamination than argon (Ar) used in percent by 70% and mixed with O_2 (30%), requiring lower power and shorter processing times to achieve the desired results. These findings suggest that cold plasma technology is a promising and innovative approach for microbial reduction in cashew nuts without compromising their quality.

Novel-assisted RF technology enhances the drying rate of ready-to-use food products while preserving heat-sensitive compounds. For instance, applying a hot air assisted radio frequency (HA-RF) for carrot slices drying, it can reduce drying time by 30% compared to hot air drying alone, with the final samples exhibiting acceptable colour, rehydration properties, and the highest total carotenoid levels (Gong et al., 2020). Du et al. (2024) applied a conjugated nisin-assisted RF technology to pre-treated carrots, resulting in significant retention of carotenoids and ascorbic acid, effective inactivation of *Staphylococcus aureus*, *Bacillus subtilis*, *E. coli*, and an extension of shelf life to 42 days. Additionally, when compared to hot water blanching, HA-RF-treated broccoli preserved better texture, bioactive compounds, and microstructure. The ascorbic acid, sulforaphane, and total glucosinolate levels in HA-RF samples were 251.1%, 131.9%, and 36.7% higher, respectively, than those in hot water blanched samples (Qing et al., 2023).

In a study, Cui et al. (2021) applied RF heating during the reheating of soymilk for packed tofu production. Computer simulations revealed that the electric field became distorted and deviated in sharp areas, leading to overheating at the edges and corners of the material. Consequently, a cylindrical container (50 mm in diameter, 100 mm in height) with minimal sharp areas was found to be the most suitable for RF heating of soymilk, as confirmed by experimental results. Additionally, packed tofu heated using RF technology at 80°C for over 20 minutes demonstrated improved texture properties, enhanced odour and taste values, and a denser network structure compared to commercially available packed tofu. These findings suggest that RF-heated packed tofu has strong consumer acceptance potential. RF heating could serve as an alternative to conventional heat treatment in packed tofu production, offering a promising approach for improved quality and efficiency.

As an alternative method, in-package RF processing was assessed for its effectiveness in inactivating *Salmonella* on black peppercorns and dried basil leaves, as well as preventing cross-contamination during storage after processing. In-package steaming involves heating the samples inside a steam vent package, which generates and retains steam throughout the treatment. This approach ensured uniform heating, likely due to steam circulation within the package. A one-way steam vent allowed excess steam to escape once a certain pressure threshold was reached and then returned to its original position to reseal the package once RF energy was removed. In-package RF steaming of black peppercorns and dried basil leaves for 135 seconds and 40 seconds, respectively, resulted in more than a 5-log reduction of Salmonella. After treatment, the steam vent remained intact and effectively sealed the package, protecting the product from external contamination (Wason et al., 2024).

Ballom et al. (2021) developed a thermal process using a pilot-scale radio frequency (RF) unit to inactivate *Salmonella* and *Listeria monocytogenes* in cocoa powder. To ensure the effectiveness of radio frequency (RF) heating for sanitizing cocoa powder, researchers tested it against two harmless bacteria, *Enterococcus faecium* and *Listeria innocua*. Heating cocoa powder to 90°C reduced *E. faecium* by approximately 1.8 log. Holding the heated powder in an insulated container for 48 minutes further decreased bacteria levels by 3.65 log. *L. innocua* proved more susceptible, showing a 5.64 log reduction after heating to 75°C followed by a shorter insulated holding period. The study concluded that *E. faecium* is a reliable indicator for assessing the process's ability to eliminate harmful pathogens like *Salmonella* and *L. monocytogenes*. Insulating the cocoa powder after RF heating is highly recommended for better microbial reduction and energy savings.

In Table 1 is presented an overview of the significant results obtained by RF heating applications in different food products treatments. These results demonstrate the effectiveness of the RF heating for food products decontamination and shelf-life extension.

Table 1. Effects of RF technology applied for thermic treatment of food products

Field	Product	Effects	Author, Year
Bakery Industry	Metallized food packaging	RF wave transmission holes placement, heating uniformity, energy efficiency optimization	(Zhang et al., 2025; Zhao et al., 2020)
	Rye bread	RF technology at 60°C, 80°C, and 100°C for fungal inhibition	(Mitelut et al., 2015)
	RF drying in cookie, cracker, cereal, and snack production	RF drying reduced moisture gradients, prevented surface cracks, improved conveyor speed, and stabilized moisture levels	(McHugh, 2016; Palamthodi et al., 2021)
	RF heating and acrylamide reduction	Incorporating RF in final baking stages with ~10% residual moisture minimized acrylamide levels	(Anese et al., 2008)
	Wheat flour	Reduction of *Enterococcus faecium*- 2.5-3.7 log a_w – 0.45 ± 0.02	(Zhang et al., 2021)
	Wheat flour	*Salmonella enteritidis* and *Enterococcus faecium* - D85°C was calculated to be 18 min to achieve 1 log reductions; 8.34 ± 0.12% (w.b.) a_w – 0.45 ± 0.02	(Liu et al., 2018a)
	Wheat germ	RF treatment reduced lipase activity by 18.2% at 100°C (15 min) and 22.5% at 110°C (5 min), enhancing wheat germ color and absorption capacity.	(Ling et al., 2019)
Meat and Fish Industry	Cooked tiger skin chicken feet	RF with ZnO NPs Pickering emulsion for microbial reduction and quality retention	(Wei et al., 2025)
	Lean beef meat	RF thawing in batch and continuous conditions, dielectric properties analysis	(Bedane et al., 2017)
	Beef sausage	Superheated water-assisted RF heating for texture, color, and microstructure improvement	(Wang et al., 2024)
	Tilapia fillets	RF-HA drying at 5, 8 and 10 mm thickness with wrapping materials	(Cao et al., 2021)

Field	Product	Effects	Author, Year
Milk Processing Industry	Dairy model systems	RF inactivation of *S. typhimurium* and *L. monocytogenes*, effect of fat content and matrix structure	(Tonti et al., 2024)
	Raw cow's milk	*Staphylococcus aureus* - 5.65 log reduction	(Soto-Reyes et al., 2022)
	Yoghurt	Destruction of yeasts and molds. LAB partially survive RF heating at 58°C and 65°C while inactivated by conventional treatment	(Altemimi et al., 2019)
	Milk	RF processing results in minimal alterations to the organoleptic properties of milk, ensuring that flavor and appearance remain largely intact	(Di Rosa et al., 2018)
Fruit and Vegetable Processing Industry	Mushrooms	RF heating effects on polyphenol oxidase (PPO) inactivation, kinetic modeling	(Pang et al., 2024; Zhang et al., 2018)
	Cashew nuts	RF cold plasma treatment for microbial decontamination and quality retention	(Ranjan et al., 2024)
	Carrot slices	HA-RF drying for reduced drying time and carotenoid preservation	(Gong et al., 2019; 2020)
	Pre-made carrots	Nisin-assisted RF technology for microbial inactivation and extended shelf life	(Du et al., 2024; Wang C. et al., 2021; Zhang R., Li, et al., 2020b)
	Broccoli	HA-RF technology for better texture, bioactive compound preservation	(Dekker et al., 2014; Qing et al., 2023)
	Soymilk for tofu production	RF heating for improved texture and sensory properties	(Cui et al., 2021)
	Black peppercorns and dried basil leaves	In-package RF steaming for *Salmonella* inactivation	(Wason et al., 2024)
	Cocoa powder	RF heating at 90°C with insulated holding for pathogen inactivation	(Ballom et al., 2021)
	Kiwi puree	The RF-treated sample retained more nutrients, had higher soluble solids, lower pH, and higher acidity than the control.	(Liu et al., 2019)
	Apple juice	RF-treated samples had similar soluble solids but higher pH than the control. RF heating preserved phenolic content and color better, with fewer objectionable components than conventional treatment	(Tian et al., 2018)
	Sweet potato	RF with hot water bleaching improved color, texture, and heating uniformity with a 90 mm gap and 60 mm thickness.	(Jiang et al., 2020)
	Soybean	RF-treated soy protein isolate had better functionality than conventional heating. RF also reduced hexanal and 1-hexanol levels, improving soy milk's sensory properties.	(Jiang et al., 2018)
	Green peas (*Pisum sativum* L.)	Increasing the temperature from 60 to 85°C significantly affected the weight, color, electrolyte leakage, and texture of peas, causing more pronounced changes.	(Zhang C. et al., 2021)
	Sweet corn (*Zea mays* L.)	RF bleaching improved texture, color, and nutrients over boiling, reducing enzymatic activity to 4.68% at 80°C.	(Sun et al., 2022)
	Pearl millet	Hot air-assisted RF treatment inactivated 97.3% of lipase in 15% hydrated millet (15 min), improving bonding and flour quality.	(Yarrakula et al., 2022)

CONCLUSIONS

Radio Frequency (RF) processing technology offers several advantages over conventional heat exchange systems in the food industry, including time savings, higher profitability, and improved efficiency in food safety under identical operating conditions. RF heating has been demonstrated to effectively eliminate pathogenic and spoilage microorganisms while preserving the physicochemical, sensory, and nutritional properties of food due to its shorter processing time.

Additionally, RF heating enables in-package processing, minimizing the risk of cross-contamination and aligning with HACCP principles (Dragoev et al., 2024).

RF processing stands as a promising alternative to conventional heating methods, offering multiple benefits, though continued advancements are necessary to overcome current challenges and optimize its use.

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