International Journal of Food Science and Nutrition
www.foodsciencejournal.com
E-ISSN: 2455-4898
Received: 25-09-2026, Accepted: 25-10-2026, Published: 09-11-2026
Volume 11, Issue 4, 2026, Page No. 125-136

Recent advances and applications of radio frequency processing in food industries: A comprehensive review

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DOI: https://doi.org/10.66856/ijfsn.2026.11.4.11200

Abstract
Radio frequency (RF) processing is an advanced, highly efficient volumetric thermal technology gaining significant interest as an alternative to conventional heating methods in the food industry. By utilizing dielectric heating principles, specifically dipole rotation and ionic depolarization. RF energy rapidly generates uniform heat directly within food matrices. This minimises processing time and protects vital quality attributes such as colour, texture, and bioactive components. This review summarizes about fundamental dielectric principles and recent hardware advancements, emphasizing widespread industrial applications including pest disinfestation, drying, post-baking, thawing, microbial reduction, and enzyme blanching. Furthermore, it addresses persistent industrial bottlenecks like non-uniform heating, elevated setup costs and high-power consumption. Finally, the review outlines future trends, highlighted by the integration of real-time monitoring sensors, and innovative hybrid thermal systems.

Keywords: Radio frequency processing, dielectric properties, volumetric heating, numerical modelling, recent trends

Introduction

Radio frequency (RF) processing or heating is one of the advanced food processing techniques gaining attention particularly for fruits and vegetables. The process is highly efficient when compared to conventional thermal methods. Radio frequency processing depends on different principles such as dielectric properties, deep penetration, geometry of foods etc. it works by generating rapid and uniform volumetric heating within the food products. This even heating is mainly achieved by dielectric heating mechanism, that is the food itself acts as a dielectric medium and absorbs energy from the RF field and converts it into heat (Shanmugam *et al*., 2025) [26]. It is mainly used as an food processing and preservation technique. When compared to other conventional methods RF treatment has better final product quality. It reduces processing time and minimizes thermal damage to the foods (D. Bermudez-Aguirre & B. A. Niemira, 2023) [3]. It offers reduced processing timing, eliminates pathogens, preserve physicochemical and sensory properties of foods, ensuring safety and stability of foods during storage (Dragoev *et al*., 2024b). One of the main limitation associated with RF is uniform heating of packed when the dielectric properties of both package and the food differ from each other (D. Bermudez-Aguirre & B. A. Niemira, 2023) [3]. There are still needs for researches in the area of permeability of the food packages and their integrity (Dragoev *et al*., 2024b) [6].

RF processing is applied in several areas within the food industry, including drying, sterilization, blanching and pasteurization. The effects of RF processed foods are generally evaluated in the basis of texture, color, and retention of bioactive components in comparison with conventional methods (Shanmugam *et al*., 2025) [26]. In addition to that RF is also effectively used for disinfection of crops, due to their selective heating phenomenon. They first inactivates insects as their dielectric properties are different from the foods (D. Bermudez-Aguirre & B. A. Niemira, 2023) [3]. Other than this RF is also used for thawing of foods, specifically in thawing of meat. It helps to reduce the mechanical damage to the muscle fiber caused by the ice crystals, which is one of the main reason for change in the texture of meat and meat products (Zhang *et al*., 2022) [18]. Future trends must tend to the development of specialized devices and optimized flow systems to achieve consistent heating uniformity. There is a need for a deeper understanding of the interaction between RF energy and the unique dielectric properties of fluid and semisolid foods matrices to accelerate biochemical reactions and compound extraction more effectively. To make RF a viable alternative process in food industry there is a need for standardized procedures (H. Zhang *et al*., 2025) [24].

Given the rapid evolution of the industry in the current world there is a critical need to synthesize recent technological innovations such as hybrid systems and real-time sensor monitoring with their practical impacts on food safety and quality. This review encompasses the fundamental dielectric principles, and the latest mechanical developments advancements in RF systems. Furthermore, the review also deals with industrial applications, including pest control, drying, thawing, microbial inactivation etc.

while addressing the current limitations and future perspectives for large scale industrial adoption.

Fundamentals of radio frequency Processing

When the food is subjected to radio frequency both ionic depolarization and dipole rotation occurs. The dipole rotation is due to the change in polarity of electro-magnetic field which makes the molecules rotate and reposition itself according to the polarity. This rapid and continuous change in position causes volumetric heat in sample and hence resulting in heat generation (Gao *et al*., 2023) [12].

1. Basic Principles

Radio frequency is simply the electromagnetic waves having frequency ranging from 10 MHz to 300 MHz. The Federal Communications Commission has restricted the frequencies of the electromagnetic waves to 13.56, 27.12, and 40.68 MHz in industrial, scientific, and medicinal uses to avoid intersection with communication systems (Y. Zhang *et al*., 2025) [24]. Radio Frequency is generated with the help of two electrodes in which one is grounded to act as a capacitor that stores electrical energy (Soto-Reyes *et al*., 2022) [27] . The power of the electromagnetic waves generated was given by the direct current that was conducted through the electrodes (Gao *et al*., 2023) [12]. Due to the depolarisation effects the molecules in the food material happens to align themselves since the positive and negative charges are present. This results in friction between the molecules that produces enormous amount of heat inside the food material (Tong *et al*., 2022) [31].

2. Dielectric Properties of food materials

The materials that poorly conducts electricity are called dielectrics. Most food products are partial conductors of electric current to a level but are classified as dielectrics. Dielectric property is a key aspect to study the behaviour of the food material under the exposure to electromagnetic energy. Upon Radio Frequency impedance, the specific dielectric property of the material determines the rate of dielectric heating. Therefore, a proper understanding of the dielectric property of food material is needed while processing using Radio Frequency technology (Teseme & Weldeselassie, 2020) [30]. The dielectric property of the food is used to describe the ability of the food material to store and dissipate the electromagnetic energy. This dielectric property (ε) is expressed in two terms as dielectric constant (ε′) and dielectric loss factor (ε″).

$$\varepsilon = \varepsilon' - j\varepsilon'' \; (j = \sqrt{-1})$$

The dielectric constant (ε′) refers to the ability of the material to store the electric field energy and the dielectric loss factor (ε″) refers to the ability of material to dissipate electric field and converting it into its own internal energy (Cheng *et al*., 2026) [5]. Numerous factors tend to influence the dielectric properties of a food material including frequency of the alternating current applied to generate the electromagnetic wave, temperature, moisture content of the food, density and the composition of the food (Sudhakar *et al*., 2023) [28]. Another property that is affected by Dielectric property is the Penetration depth (P_d). It also depends on the frequency of the wave.

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

Where, c - The speed of light in vacuum (3 x 10^8 m/s), f – Frequency (Hz)

With the above equation it is clear that higher frequency directly provides smaller penetration depth (P_d) in food material where the dielectric properties are kept constant. It helps in determining the required thickness of the food material that needs to be processed using Radio Frequency to make sure uniform heating (Das *et al*., 2025); (Y. Zhang *et al*., 2025) [8, 24].

Dielectric properties in food materials differs from product to product. In grains, the dielectric properties are based on the moisture content, frequency used and the temperature. In baked products, the behaviour is characterized by an increased dielectric constant and decreased loss factor where the moisture content has no influence over loss factor in baked products. In the macaroni and cheese products the dielectric constant decreased with increasing temperature whereas the loss factor increased at higher frequencies. Dielectric properties tend to change in butter based on the salted and unsalted varieties. This is because although the dielectric properties are greatly influenced by the moisture content other factors like salt content and minerals also has effect over dielectric properties. Eggs has increasing dielectric constants and loss factor with increasing temperatures at 27 MHz. In fruit and vegetables, the dielectric constant increases and loss factor decrease with increasing moisture content (Teseme & Weldeselassie, 2020) [30].

3. Mechanism of heat generation

Heat generation upon application of radio frequency waves in food takes place in two ways: 1. Bipolar polarisation and 2. Ionic Conduction.

The electromagnetic field polarizes the H_2O molecules and other polar molecules in food which is termed as bipolar polarization and the molecules that are non-polar gets induced with dipoles that is associated with the electric field voltage. The molecular mass greatly influences the bipolar polarization along with the electromagnetic frequency factors. Food containing lower molecular weighing particles are less interactive with the frequency of the Radio Frequency treatment. Another way of heat generation is by the alternating electric field that makes the charged ions migrate towards the opposite polarity due to Ionic

Conductivity. This is expressed by ions that are electrically charged as positive and negative charges due to the polarization effect resulting in collision with dipole molecules like H_2O molecules. The movement of the ions are reversed as there is a change in the polarity of the ions. This rapidness of this continuous movement differs with the frequency applied. The frictional force between the molecules upon the movement results in the heat generation (Dragoev *et al*., 2024a)

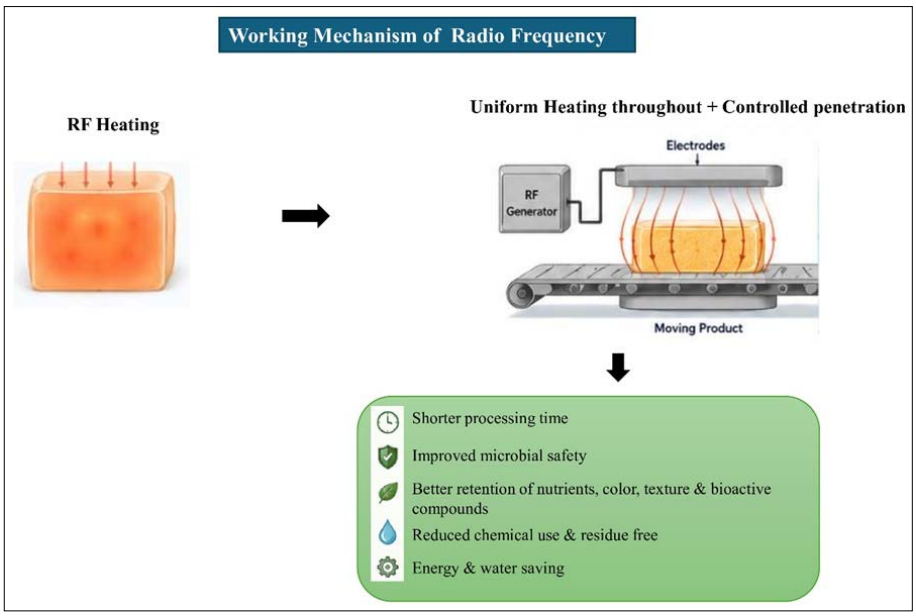


Fig 1: Mechanism of heat generation in RF heating

Major applications in food industries

Recently, Radio Frequency (RF) heating has been extensively applied in the processing of food and agricultural products for operations such as Blanching, Pasteurization, Drying and Thawing and so on (Cui *et al*., 2021) [7]. It is considered a promising alternative to conventional thermal processing methods because of its rapid volumetric heating capability and greater penetration depth. In conventional heating systems, heat is transferred from the product surface toward the interior, resulting in slower heat transfer within the product. Consequently, the outer regions may become overprocessed while colder zones remain inside. In contrast, RF processing exposes the entire product volume to a relatively uniform electromagnetic field. The penetration depth influenced by operating frequency and dielectric properties such as dielectric constant and loss factor, promotes more uniform temperature distribution throughout the material. As a result, RF processing enhances process efficiency, improves food safety, and effectively achieves the intended quality and preservation objectives (Saka *et al*., 2021) [25].

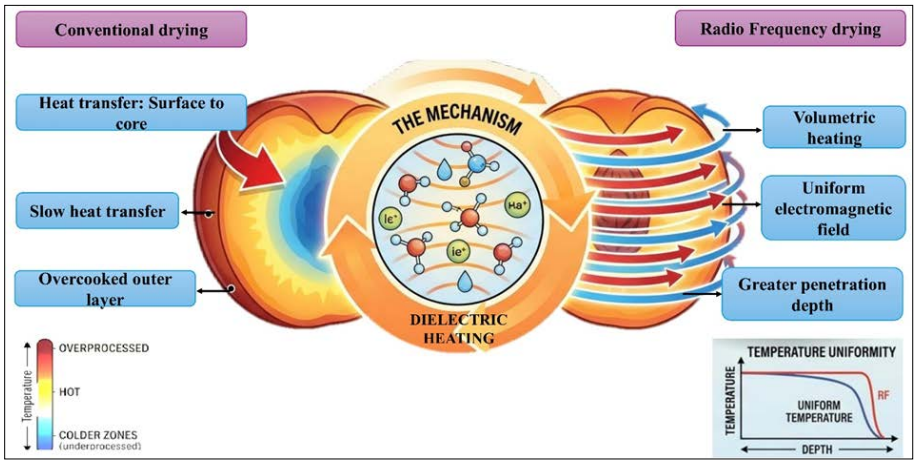


Fig 2: Comparison between conventional and radio-frequency drying

1. Disinfection and disinfestation

RF heating is an effective method for food disinfestation with added quality benefits (Appugol *et al*., 2022) [2]. A study conducted by Appugol *et al*., using a 10 kW, 40.68 MHz system at 180 mm electrode height and 5 m/h, peanuts reached 89.96°C in 5-8 min, achieving 100% mortality of *Caryedon serratus* (adults in 24h; eggs in 60 days). Rf also reduced Aflatoxin B1 by 92.64% and B2 by 90.51%. Moisture decreased from 7.5% to 2.11% protein slightly from 22.17% to 20.94%, while oil yield increased from 51.3% to 70.31%. Color remained stable. Oil quality showed slight increases in Free fatty acid (0.55%), Acid

value (0.82 – 1.09 mg/g), and Peroxide value (0.87 – 1.61 meq O_2/kg), all within Codex limits. Overall, RF is a rapid, efficient disinfestation technique with minimal quality loss.

In another study, Mangang *et al*. evaluated RF heating as a non-chemical disinfestation method for turmeric powder infested with *Lasioderma serricorne*. Using a 10 kW, 40.68 MHz RF system, rapid mortality was achieved across all life stages. At 180 mm electrode height, the lowest Lethal Doses (LD) were recorded: Eggs (LD_{50} 1.96 min; $LD_{99.99}$ 5.34 min), Larvae (LD_{50} 2.04 min; $LD_{99.99}$ 4.77 min), Pupae (LD_{50} 2.13 min; $LD_{99.99}$ 5.91 min) and Adults (LD_{50} 2.13 min; $LD_{99.99}$ 6.06 min). Increasing electrode height to 225 mm increased exposure time (eg., pupae $LD_{99.99}$ up to 13.96 min), though 100% mortality was achieved at 25 m/h. Importantly, RF preserved food quality, with minimal changes in protein, fat, curcumin and ash contents. Key bioactive compounds were retained. Thus, RF offers rapid, residue-free, and efficient disinfestation, making it a promising alternative to chemical fumigation in food processing (Mangang *et al*., 2022) [2].

2. Drying and post-baking

According to Ismail. M, *et al*., Hot ir-assisted RF drying of orange slices significantly improved drying efficiency and product quality compared with conventional hot air drying. The optimum condition was a 70 mm electrode gap with three slices (12mm thickness). Drying time was reduced by 67% from 1170 min in hot air drying to 390 min, due to the higher drying rate and faster moisture diffusion (2.48×10^{-9} m^2/s). The technique also provided better retention of Total Phenolic Content, Antioxidant activity, Vitamin C (173 mg/100g dry weight), and color stability and bulk stability. Considering the short drying time and high drying rate, Hot Air-assisted RF drying can be used as an effective alternative technique for drying oranges (Ismail *et al*., 2024) [15]

In another study, Mahmood, N., *et al*., evaluated Hot Air-assisted RF drying of brown rice using a 27.12 MHz, 6 kW RF system at electrode gap of 100-120 mm, temperatures of 50-60 °C, and air velocities of 0.5-2.5 m/s. Fresh rice with 25.5 ± 0.5% Moisture content (wet basis) was dried to 13.0 ± 0.5%. Optimum conditions were 110 mm (electrode gap), 60°C, and 2.5 m/s. Results showed amylose content ranged from 283.23 to 303.22 mg/g, with no significant difference between Hot Air drying and Hot Air-assisted RF drying at optimal conditions. Gel consistency ranged between 82-92 mm, indicating soft cooking quality. Hot Air-assisted RF drying reduced cooking time, increased protein solubility and improved volume expansion ad water adsorption compared to Hot Air drying. Overall, Hot Air-assisted RF drying enhances cooking and functional properties without compromising nutritional quality, making it a promising Post harvest technology (Mahmood *et al*., 2023) [20].

In the study conducted by Saka, I., *et al*., RF treatment maintained most physicochemical and rheological properties of wheat flour, while moderate treatments up to 65°C caused minimal changes in bread quality. This indicates that RF can effectively improve product safety while preserving, texture, color and nutritional properties. However, higher RF treatments (75-85°C) increased bread hardness and reduced loaf volume due to gluten structural modifications. Therefore, in post baking applications, optimization of RF temperature, exposure time and product moisture is essential to achieve microbial safety while maintaining desirable sensory and structural quality of bakery products (Saka *et al*., 2021) [25].

3. Thawing and tempering

RF thawing is widely used for defrosting meat, seafoods, fruits and vegetables (Dong *et al*., 2021) [9]. However, a major limitation of RF heating is the non-uniform temperature distribution within the product during thawing. This occurs because the dielectric properties of frozen and thawed regions differ significantly. As a result, thawing may take longer and can lead to quality deterioration and increased risk of bacterial growth. Liu, X, *et al*., demonstrated superior performance of RF heating in thawing frozen strawberries, achieving rapid thawing (300 s at 12 cm gap) through efficient volumetric heating. It better preserved microstructure, firmness (0.90 – 1.11 kg/cm ^{2}), and minimized drip loss (2.9 – 5.6%) compared to Microwave and Refrigerator thawing, though smaller electrode gaps caused more structural damage. RF thawing maintained higher Total Soluble Solids (9.4 – 9.8%) with no major differences in Titratable Acidity and Microbial safety. It also showed improve color retention and higher preservation of bioactive compounds. Antioxidant activity remained significantly higher in RF thawing, confirming its effectiveness in maintaining overall quality attributes (Liu *et al*., 2024) [17].

Similarly, Frozen ground beef blocks with varying water, fat, and salt contents were thawed using a 6 kW, 27.12 MHz parallel plate RF system with a 10 cm electrode gap. RF thawing of ground beef reduced thawing time to <100 min (-20 to 0°C) versus 5 h (water) and 48 h (air), though edge heating caused higher temperatures at corners. Heating rates increased with water (4.7 – 5.8 °C/min) and fat (6.1 – 7.9 °C/min) but decreased with salt (3.5 – 0.2 °C/min). Color analysis showed **L* increased with water and fat but decreased with salt, **a* increased with salt, and **b* remained unchanged. Overall, RF thawing is rapid and effective, but optimal uniformity is achieved with lower water and fat, and higher salt levels (Dong *et al*., 2021) [9].

The study on Salmon conducted by Han, R, *et al*., compared RF Tempering (RT: 40.68 MHz, 400 W, 122 mm) with Water Tempering (WT: 10 ± 0.5°C) and Air Tempering (AT: 10 ± 1°C) from -20 to 4 °C. RT completed tempering in 5 min, while WT and AT required 15 min and 64 min (3 and 12.8 times slower) due to conduction and convection limits. Dielectric properties increased from -20 to 20 °C, sharply at – 10 to -5 °C, causing edge overheating; penetration depth was highest at 13.56 MHz, followed by 27.12 MHz, and lowest at 40.68 MHz. Surface temperatures (top/bottom) were 7.3/13.4 °C (RT). 11.8/8.4 °C (WT), and 7.2/2.2 °C (AT), showing best uniformity in AT. Thiobarbituric Acid Reactive Substances (TBARS) values were 1.027 (control), 3.102 (WT), 2.135 (RT) and 1.054 mg MDA/kg (AT). Overall, AT gives best quality but is slow, while RT offers rapid tempering with acceptable quality (Han *et al*., 2022) [13].

4. Microbial inactivation

Radio frequency heating used to eliminate microorganisms (pathogenic and putrefactive) and it reduces the loss of food quality characteristics. It inactivates microorganisms by conventional thermal mechanisms, mainly denaturation of enzymes, proteins and nucleic acids. Nuclei acids of microorganisms are denatured at high temperatures as a

result double stranded DNA becomes single stranded because of breaking hydrogen bonds between the bases forming the strands. Radio frequency inactivates fungi by thermal disruption, degradation of DNA, proteins, and lipids results in cell rupture and viruses by inhibits host cell recognition/binding and induces structural changes in viral protein (Dragoev *et al*., 2024a). The low temperature, long-term RF pasteurization inactivates Samonella Enteritidis in onion powder. The RF heating reached at 66°C in 190 s. After 38 h of treatment, they found 3.4 log reduction of microbial populations. After this process the quality of the onion powder was good without any change after the process (Liu *et al*., 2022) [18].

Radio frequency heating applied to in-shell eggs. It inactivates salmonella Typhimurium with radio frequency at 40.68MHz, 35W, for 4.5 min use cooling water (38°C), applied on top of eggs during RF treatment. It achieved 5-log reduction of microbial population in in-shell eggs (D. Bermudez-Aguirre & B. Niemira, 2023) [3]. Radio frequency heating applied to determine the effect of milling degree(MD) of rice on heating rate and pathogen inactivation of Salmonella typhimurium and Staphylococcus aureus and color change. Rice samples are heating for 0 to 75 s. In Radio frequency heating, the highest heating rate observed in 2% MD rice. The time required to reach 90°C for 2% MD rice is 56 s. they found 5.76 log reduction of Salmonella Typhimurium for 75 s RF heating. They achieved the 5.03 log reduction of Salmonella aureus for 75 s heating of RF heating. The color of rice samples was not changed after RF heating (Jeong *et al*., 2022) [16].

5. Enzyme inactivation and blanching

Enzymatic browning causes discoloration in horticultural crops and minimally processed products. Polyphenol oxidase (PPO) is the key enzyme responsible for enzymatic browning. PPO is caused by damage in cell membrane because of post-harvest senescence, biotic and abiotic stress as result of this produces darkened tissue. Polyphenol Oxidase reacts with endogenous phenols to form quinones after it polymerize to give brown pigments on the surface of fresh and fresh-cut fruits and vegetables products. As a result of this reduction in quality, sensory and nutritional benefits of fruits and vegetables (Sui *et al*., 2023) [29]. Steam (ST)- assisted radio frequency blanching is used for fresh-cut stem lettuce cuboids. It combines the steam blanching and RF preheating gives better heating uniformity and physicochemical properties than single steam blanching and RF heating. It reduces the waste of water during blanching. RF heating combined with steam blanching could produce uniform temperature and reduce the damage. The best combination of RF at 80°C and ST for 1 min gives the most uniform temperature distribution and reducing the time taken for inactivate enzyme. The blanched stem lettuce was greener and less yellow, and it causes lesser color difference than single steam and RF blanching (Yao *et al*., 2022) [33].

Radio frequency (RF) combined with steam blanching gives rapid and effective inactivation of polyphenol oxidase (PPO) of iron yam (Dioscorea opposite Thunb). It combines RF with saturated steam blanching (SS) (100°C) and super-heated steam blanching (SSB) (110°C). Combination of RF and SSB blanching takes only 45 s to reduce PPO residual activity <5%. It maintains the best color, and texture (hardness, fracturability, chewiness) with lower relative electrolyte leakage (REL), higher retention of vitamin C and minimal cell disruption of the yam. It enhances the enzyme inactivation efficiency and increases the quality of fruits and vegetables (Pang *et al*., 2025) [24]. Radio frequency (RF) combined with hot water (HW) blanching for broccoli samples (whole florets, quartered pieces, and bud florets). The combined RF (6KW, 27.12MHz RF system) with hot water blanching inactivates peroxidase activity in addition to it reduces the blanching time by 30%, 50.8% and 32.3% for whole florets, quartered pieces and bud florets. It decreases weight loss to 62.5%, 41.1% and 57.1% and it minimizes loss of vitamin C by 22.0%, 14.3% and 21.7%. It increases the efficiency of energy to 120.0%, 113.3% and 103.1% and preserve hardness by 50.1%, 13.5% and 17.6%. The combination of RF and HW blanching maintain the product quality and color at various broccoli cut sizes (Wang *et al*., 2025) [32].

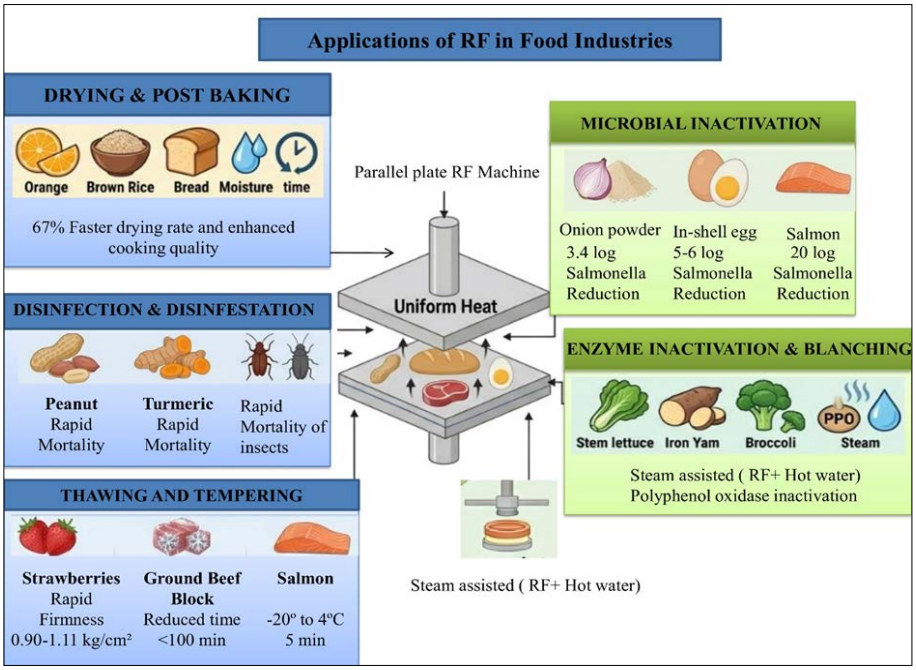


Fig 3: Applications of RF in the food industry

Table 1: Comprehensive Summary of Radio Frequency (RF) Heating Applications in Food Industries

Application	Food / Product	Operating Parameters & System Details	Outcomes	Impact on Quality, Nutrition & Physical Properties	Reference
Disinfection & Disinfestation	Peanuts	10 kW, 40.68 MHz system; 180 mm electrode height; 5 m/h conveyor speed; 5–8 min exposure time.	Reached 89.96°C; achieved 100% mortality of *Caryedon serratus* (adults in 24h; eggs in 60 days); reduced Aflatoxin B1 by 92.64% and B2 by 90.51%.	Moisture decreased (7.5% to 2.11%); protein slightly fell (22.17% to 20.94%); oil yield increased (51.3% to 70.31%). Color remained stable; slight increases in FFA (0.55%), Acid value (0.82–1.09 mg/g), and Peroxide value (0.87–1.61 meq O_2/kg) remained within Codex limits.	(Appugol *et al*., 2022) [2]
Disinfection & Disinfestation	Turmeric powder	10 kW, 40.68 MHz RF system; 180 mm & 225 mm electrode heights; 25 m/h speed. Infested with *Lasioderma serricorne*.	Reached 100% mortality across all life stages. Lowest Lethal Doses (LD99.99) at 180 mm: Eggs (5.34 min), Larvae (4.77 min), Pupae (5.91 min), Adults (6.06 min). 225 mm gap increased pupae LD99.99 up to 13.96 min.	Preserved food quality with minimal changes in protein, fat, curcumin, and ash contents; key bioactive compounds were retained. Residue-free processing.	(Mangang *et al*., 2022) [2]
Drying & Post-baking	Orange slices	Hot air-assisted RF drying; 70 mm electrode gap; three slices used (12 mm thickness).	Drying time reduced by 67% (from 1170 min in conventional hot air to 390 min) due to a higher drying rate and faster moisture diffusion ($2.48*10^{-9}$ m^2/s).	Better retention of Total Phenolic Content, Antioxidant activity, and Vitamin C (173 mg/100g dry weight); provided excellent color stability and bulk stability.	(Ismail *et al*., 2024) [15]
Drying & Post-baking	Brown rice	Hot air-assisted RF drying; 27.12 MHz, 6 kW system; 100–120 mm electrode gap (110 mm optimum); 50–60°C (60°C optimum); 0.5–2.5 m/s air velocity (2.5 m/s optimum).	Fresh rice dried from 25.5 ± 0.5% moisture content (wet basis) down to 13.0 ± 0.5%. Reduced overall cooking time.	Amylose content (283.23 to 303.22 mg/g) showed no significant difference from hot air drying. Gel consistency (82–92 mm) indicated soft cooking quality. Increased protein solubility, volume expansion, and water adsorption.	(Mahmood *et al*., 2023) [20].
Drying & Post-baking	Wheat flour / Bread	Post-baking treatment; moderate treatments up to 65°C versus high treatments (75–85°C).	Effectively improves microbial product safety, but requires precise optimization of temperature, exposure time, and product moisture.	Moderate heating (65°C) maintained most physicochemical/rheological properties and bread quality. Higher treatments (75–85°C) increased bread hardness and reduced loaf volume due to gluten structural modifications.	(Saka *et al*., 2021) [25]
Thawing & Tempering	Frozen strawberries	12 cm electrode gap; 300 s exposure time. Evaluated against Microwave and Refrigerator thawing.	Achieved rapid thawing through efficient volumetric heating.	Better preserved microstructure, firmness (0.90–1.11 kg/cm^2), and minimized drip loss (2.9–5.6%). Maintained higher Total Soluble Solids (9.4–9.8%), improved color retention, higher antioxidant activity, and preservation of bioactive compounds. Smaller gaps caused more structural damage.	(Liu *et al*., 2024) [17].
Thawing & Tempering	Frozen ground beef blocks	6 kW, 27.12 MHz parallel plate RF system; 10 cm electrode gap. Blocks varied in water, fat, and salt content.	Reduced thawing time from -20ºC to 0 ºC to <100 min (compared to 5 h for water and 48 h for air). Edge heating caused corner	Color analysis: L* increased with water/fat but decreased with salt; a* increased with salt; b* remained unchanged. Best heating uniformity achieved with lower water/fat and higher salt levels.	(Dong *et al*., 2021) [9].

			overheating. Heating rates increased with water and fat but decreased with salt.		
Thawing & Tempering	Salmon	RF Tempering (RT: 40.68 MHz, 400 W, 122 mm) compared with Water Tempering (WT) and Air Tempering (AT) from -20 ºC to 4 ºC.	RT completed tempering in 5 min (3 times faster than WT at 15 min; 12.8 times faster than AT at 64 min). Dielectric properties spiked sharply between -10ºC and -5 ºC, causing edge overheating.	Surface temperatures (top/bottom) were 7.3/13.4°C (RT), 11.8/8.4°C (WT), and 7.2/2.2°C (AT), with AT showing best uniformity. TBARS values (mg MDA/kg): 1.027 (control), 3.102 (WT), 2.135 (RT), 1.054 (AT). RT yields acceptable quality rapidly.	(Han *et al*., 2022) [13]
Microbial Inactivation	Onion powder	Low-temperature, long-term RF pasteurization; reached 66°C in 190 s; 38 h total treatment time.	Achieved a 3.4 log reduction of *Salmonella Enteritidis* population.	Quality of the onion powder remained good and was completely unchanged after the process.	(Liu *et al*., 2022) [18]
Microbial Inactivation	In-shell eggs	40.68 MHz, 35W system; 4.5 min exposure; cooling water (38°C) applied on top of eggs during treatment.	Achieved a 5-log reduction of *Salmonella Typhimurium* microbial population.	Target microbial inactivation accomplished via conventional thermal mechanisms (denaturation of enzymes, proteins, and nucleic acids).	(D. Bermudez-Aguirre & B. Niemira, 2023) [3].
Microbial Inactivation	Rice (varying Milling Degrees - MD)	RF heating for 0 to 75 s to analyze the effect of Milling Degree (MD) on heating rate.	Reached 90°C in 56 s for 2% MD rice (highest heating rate). 75 s of RF heating achieved a 5.76 log reduction of *Salmonella Typhimurium* and a 5.03 log reduction of *Staphylococcus aureus*.	Color of the rice samples was not changed after RF heating.	(Jeong *et al*., 2022) [16]
Enzyme Inactivation & Blanching	Fresh-cut stem lettuce cuboids	Steam (ST)-assisted RF blanching (combines RF preheating with steam blanching). Best combo: RF at 80°C + ST for 1 min.	Provides better heating uniformity and reduces enzyme inactivation time compared to single steam blanching or standalone RF heating. Reduces water waste.	Inactivates Polyphenol oxidase (PPO); produces uniform temperature with less structural damage. Blanched lettuce was greener, less yellow, and exhibited lesser color differences than single methods.	(Yao *et al*., 2022) [33]
Enzyme Inactivation & Blanching	Iron yam (*Dioscorea opposita* Thunb)	RF combined with Saturated Steam blanching (SS at 100°C) or Super-heated Steam blanching (SSB at 110°C).	Combination of RF and SSB took only 45 s to reduce PPO residual activity to <5%, maximizing enzyme inactivation efficiency.	Maintains the best color and texture (hardness, fracturability, chewiness). Results in lower relative electrolyte leakage (REL), higher retention of vitamin C, and minimal cell disruption.	(Pang *et al*., 2025) [24]
Enzyme Inactivation & Blanching	Broccoli (whole florets, quartered pieces, bud florets)	Combined RF (6 kW, 27.12 MHz RF system) with hot water (HW) blanching.	Reduced blanching times by 30% (whole), 50.8% (quartered), and 32.3% (buds). Increased energy efficiency by 120.0%, 113.3%, and 103.1% respectively.	Inactivates peroxidase activity; decreases weight loss (to 62.5%, 41.1%, 57.1%); minimizes Vitamin C loss (by 22.0%, 14.3%, 21.7%); and preserves product hardness (by 50.1%, 13.5%, 17.6%) and color across various cut sizes.	(Wang *et al*., 2025) [32]

Recent Technological Advances in RF Systems

Other than baking and drying RF systems as diversifying applications leading to development in advanced techniques, such as using numerical simulations to optimize equipment design, such as strategically placing wave transmission holes in metal susceptors and utilizing physical field combinations. The recent trend follows hybrid approaches such as combining RF with hot air to increase drying rates etc. (MITELUȚ *et al*., 2025) [22]. Further advancements are elaborated in the section below.

1. Innovations in electrode designs

In RF processing adjusting the dimensions of the top and bottom electrodes to be larger than the material being treated which helps to maintain high heating rates at the same time improving the uniformity of temperature distribution. Optimizing the electrode size 1.2 times more than the normal electrode to material size ratio has significantly reduced the overheating of electrodes in the edges. And the implementation of reverse cycle i.e., where the orientation of the product or electric field is periodically shifted during the heating process, which stabilizes the electromagnetic field distribution. This combined advancement in electrode and processing cycle result in a more efficient energy transfer to the food matrix, reducing overall power consumption and ensuring that the final product meets safety and quality standards without any thermal damage (Lei *et al*., 2024) [17]. Advanced electrode technologies include specialized configurations such as bipolar, cluster, cooled-tip and expandable electrodes. The cooled-tip during energy delivery circulates the water internally to keep the electrode tip cool. This prevents excessive heat accumulation at the tips (Zhitny *et al*., 2024) [37].

The advancements in electrode designs helps in overcoming the challenge of non-uniform heating in RF processing. Electrodes such as curved, steeped and spherical are specifically designed of food applications. They ensure to align with the irregular geometry of the food products. This designs redistribute the electric field more evenly across the material specifically from the edges and corners where the over heating occurs. The use of multi-electrode systems and the optimization of the air gap between the electrode and the product results in control over the power density and temperature (Costa & Marra, 2024) [6]. The recent advancement in includes customized electrode geometries to match the specific profiles of the food product for the better distribution of electric field. A significant development in this field is use of auxiliary electrodes or also known as “guard rings”. These are wave transmission holes within the electrode structure helps in precise control over heat generated during RF processing (MITELUȚ *et al*., 2025) [22]. With the help of fluid dynamics and electromagnetic modelling to refine these electrode shapes and placements, the technology has advanced its capability to achieve consistent microbial and enzymatic inactivation as well as pest control without compromising the overall quality or sensory attributes of the food matrix (Costa & Marra, 2024) [6].

2. Hybrid systems

To overcome limitations such as single source heating, lack of surface moisture evaporation, hybrid systems or combined approaches comes in act. RF is combined with different methods such as Hot air drying, vacuum heating, infrared treatment, which are considered as effective methods to preserve the nutritional profiles of fruits and vegetables. Hot air integrated with RF (RF-HA) facilitates rapid removal of moisture from the product surface and the RF provides deep volumetric heating (Shanmugam *et al*., 2025) [26]. RF-HA uses forced convection to stabilize surface temperatures and accelerate moisture evaporation. RF integrated Infrared (RF-IR) provides rapid surface heating complement the internal volumetric heating (Y. Zhang *et al*., 2025) [24]. Combining vacuum with RF gives lower-temperature processing, which is crucial for maintaining the structural integrity and antioxidant capacity of high moisture products (Shanmugam *et al*., 2025) [26]. Researchers consider combination of RF with vacuum or cold plasma as “intelligent” hybrid systems. These technologies help in low-temperature pasteurization and drying thereby protecting the sensory attributes and bioactive compounds of heat sensitive foods (Y. Zhang *et al*., 2025) [24].

A study by Huang *et al*., (2024) [14] on RF processing of Ready-to-eat foods reveals that hybrid technologies are essential for maintaining the high-quality standards required for ready-to-eat (RTE) foods which contains complex and multi component ingredients. There are synergic effects between RF and several novel assistants, such as hot air (RF-HA), which effectively prevents moisture condensation on the food surface, and RF-vacuum (RF-V) heating, which facilitates moisture evaporation at lower temperatures to protect heat-sensitive nutrients and textures. The integration of RF with microwave (RF-MW) and infrared (RF-IR) systems to create a more uniform thermal field, as well as the use of ultrasound-assisted RF to enhance mass transfer and microbial inactivation rates. These hybrid approaches are shown to significantly reduce the processing time compared to conventional retort methods, thereby minimizing the "over-processing" of RTE meals and ensuring that the sensory characteristics, such as color, flavor, and mouthfeel, are preserved while achieving the necessary shelf-life stability and pathogen reduction (Huang *et al*., 2024) [14].

By coupling RF with these external energy sources, the processing time is significantly shortened and the thermal lethality against pathogens is more evenly distributed throughout the product, effectively overcoming the limitations of single-mode dielectric heating and ensuring higher overall food quality and safety (Y. Zhang *et al*., 2025) [24]. These hybrid techniques are presented as a superior alternative to traditional blanching and hot-water treatments, as they achieve enzymatic and microbial inactivation while minimizing the leaching of water-soluble nutrients and maintaining the natural color and texture of the produce (Shanmugam *et al*., 2025) [26].

Table 2: Technological Advances in Radio Frequency (RF) Systems

Major System Categorization	Specific Configuration	Operating Parameters,	Outcomes	Quality, Sensory, & Nutritional Impact	Reference
Innovations in Electrode Designs	Reverse Cycle Processing	The orientation of the food product or the electric field is periodically shifted during the heating process.	Stabilizes the electromagnetic field distribution. Results in a more efficient energy transfer to the food matrix and reduces overall power consumption.	Ensures the final product meets safety and quality standards without causing any thermal damage.	(Lei *et al*., 2024) [17]
Innovations in Electrode Designs	Advanced Specialized Configurations (Bipolar, cluster, cooled-tip, and expandable electrodes)	The cooled-tip configuration internally circulates water during energy delivery to keep the electrode tip cool.	Prevents excessive heat accumulation specifically at the electrode tips.	Helps in overcoming the persistent challenge of non-uniform heating in RF processing.	(Zhitny *et al*., 2024) [37]
Innovations in Electrode Designs	Customized & Shaped Geometries (Curved, stepped, and spherical electrodes)	Specifically designed to align with the irregular geometry and specific profiles of food products. Optimizes the air gap between the electrode and the product.	Redistributes the electric field more evenly across the material, particularly at edges and corners where overheating typically occurs. Provides precise control over power density and temperature.	Achieves consistent microbial and enzymatic inactivation as well as pest control without compromising the overall quality or sensory attributes of the food matrix.	(Costa & Marra, 2024) [6]
Innovations in Electrode Designs	Auxiliary Electrodes / Guard Rings	Utilizes wave transmission holes within the electrode structure , refined using fluid dynamics and electromagnetic modeling.	Allows for precise control over the heat generated during RF processing.	Refines heat generation to protect the overall quality and sensory attributes of the food matrix during treatment.	(Costa & Marra, 2024; MITELUȚ *et al*., 2025) [6, 22]
Hybrid Systems / Combined Approaches	RF Integrated with Hot Air (RF-HA)	Combines RF deep volumetric heating with forced convection hot air drying.	Facilitates rapid removal of moisture from the product surface, stabilizes surface temperatures, and accelerates moisture evaporation. Effectively prevents moisture condensation on the food surface. Increases drying rates.	Preserves the nutritional profiles of fruits and vegetables. Minimizes "over-processing" of complex ready-to-eat (RTE) meals, preserving color, flavor, and mouthfeel.	(MITELUȚ *et al.*, 2025) (Shanmugam *et al*., 2025) (Huang *et al*., 2024) [14, 22, 26]
Hybrid Systems / Combined Approaches	RF Integrated with Infrared (RF-IR)	Integrates RF internal volumetric heating with rapid surface heating provided by infrared treatment.	Creates a more uniform thermal field throughout the product. Significantly shortens processing time compared to conventional retort methods.	Ensures thermal lethality against pathogens is evenly distributed. Avoids single-mode dielectric heating limitations to maintain high food quality and safety.	(Huang *et al*., 2024) (Y. Zhang *et al*., 2025) [14, 24].
Hybrid Systems / Combined Approaches	RF Combined with Vacuum (RF-V)	Combines RF with vacuum heating; considered an "intelligent" hybrid system.	Lowers processing temperatures while facilitating efficient moisture evaporation. Achieves low-temperature pasteurization and drying.	Crucial for maintaining structural integrity, protecting heat-sensitive nutrients/textures, and preserving the antioxidant capacity of high-moisture, heat-sensitive foods.	(Shanmugam *et al*., 2025) (Y. Zhang *et al*., 2025) [24, 26].
Hybrid Systems / Combined Approaches	RF Combined with Cold Plasma	Synthesizes RF with cold plasma as an "intelligent" hybrid system.	Performs processing and pasteurization at lower temperatures.	Protects and maintains the vital sensory attributes and bioactive compounds of heat-sensitive foods.	(Y. Zhang *et al*., 2025) [24].
Hybrid Systems / Combined Approaches	RF Integrated with Microwave (RF-MW)	Integrates radio frequency systems directly with microwave energy systems.	Creates a highly uniform thermal field within the food matrix. Delivers even distribution of thermal lethality against pathogens.	Minimizes leaching of water-soluble nutrients and protects natural color/texture compared to traditional retort or hot-water treatments.	(Huang *et al*., 2024) (Y. Zhang *et al*., 2025) [14, 24].
Hybrid Systems / Combined Approaches	Ultrasound-Assisted RF	Combines ultrasound technologies directly with radio frequency processing.	Enhances mass transfer rates and accelerates microbial inactivation rates. Significantly shortens overall processing time.	Serves as a superior alternative to traditional blanching by achieving enzymatic and microbial inactivation while minimizing nutritional leaching and texturing changes.	(Shanmugam *et al*., 2025) (Huang *et al*., 2024) [14, 26]

3. Real-time monitoring

Radio frequency identification technology is transforming the food industry by allowing businesses to track and monitor food products in real time without needing any barcodes. By using cheap, wireless and battery-free tags attached to packaging, companies can instantly track inventory, monitor warehouse shipments and quickly detect temperature changes in the cold chain to prevent food from spoiling. Additionally, these smart tags can be combined with special sensors to monitor chemical changes and early signs of food rot directly inside the package. When connected to digital networks, this radio frequency technology creates an automated system that keeps food fresh, reduces waste and ensures safety all the way from the farm to the consumer (Mostaccio *et al*., 2023) [23]. In a recent study of integrating RF with chemiresistive nanomaterials specifically a single walled carbon nanotube composite to function on the operational principle of chemically actuated resonant devices (CARDs). As meat or seafood samples stored inside a package begin to spoil, they release volatile amines like ammonia, which interact directly with the chemiresistive layer on the flexible, lithographically fabricated RF tag. This chemical interaction alters the electrical resistance of the composite material, establishing a direct correlation between the sensor's electronic profile and the attenuation of the radio frequency signal measured through the reflection coefficient. Consequenctly, real time monitoring of food quality is achieved through a systematic, gradual decrease in the RF signal's amplitude and peak resonant frequency, offering a scalable, affordable, and portable method to continuously track cumulative gas exposure and preserve food safety across the supply chain (Andre *et al*., 2024) [1].

Challenges and limitations

Although we have discussed various aspects of radio frequency processing in this review there are various challenges in implementing the technology in commercial scale. Radio frequency processing has a gap in direct industrial application due to its lesser uniformity in heating of food materials that results in two major defects namely underheating and overheating. This non-uniform heating ends in improper inhibition of microorganisms and also forms undesirable compounds like acrylamides. Studies are going on by applying AI and IoT technologies to enhance the Radio Frequency distribution by evaluating the temperature and moisture content in real time (Y. Zhang *et al*., 2025) [24]. It requires more comprehensive data on the dielectric properties of various food materials with respect to the size, dimensions and placement of the Radio Frequency generating electrodes to get uniform heating throughout the food product (Costa & Marra, 2024) [6]. The uneven distribution of moisture content and salt concentration along the food materials also leads to non-uniform heating in radio frequency processing (Dong *et al*., 2021) [9]. Radio Frequency processing equipment also has a higher erection cost in industrial scale when comparing to conventional processing systems. Higher power consumption is another major factor that makes the technology unsustainable. To improve the efficiency of the radio frequency processing, it is combined with other processing aids like vacuum, hot air, cold plasma, etc. (Y. Zhang *et al*., 2025) [24].

Future perspectives

Future researches on RF processing should focus on developing customized heat strategies tailored specifically to the diverse physicochemical, structural and dielectric properties of distinct food materials. A primary area for innovation is in the design of hybrid systems that combine RF heating with complementary processing technologies such as plasma treatment, cold shock, ultraviolet irradiation, ultrasound, infrared heatinf and high hydrostatic pressure processing to maximize the thermal efficiency while mitigating localized overheating or cold spots. Furthermore, the future of RF technology depends on interdisciplinary advancements, particularly the integration of intelligent control system, machine learning algorithms and real-time numerical optimizations. By embedding these algorithmic framework with mechanistic models, industry can create highly precise automated and adaptive thermal processing environments that ensure uniform energy distribution, optimize power efficiency and maintain the sensory, nutritional and structural quality of food products (Y. Zhang *et al*., 2025) [24]

Conclusion

Radio frequency technology represents a powerful, rapid alternative to traditional surface-to-core thermal methods, significantly improving both process efficiency and final food preservation quality. However, achieving consistent, wide-scale commercial adoption requires overcoming non-uniform heat distribution driven by complex shape variations and uneven moisture or salt levels across different food matrices. Recent technological innovations, particularly customized electrode structures and hybrid processing methods (such as combining RF with hot air or vacuum), offer promising solutions to eliminate localized thermal damage. Moving forward, the industrial viability of RF processing depends heavily on establishing standardized procedures, building detailed dielectric data frameworks, and integrating intelligent control networks like machine learning and real-time smart sensor systems. Ultimately, these interdisciplinary advancements will establish RF as a highly precise, automated, and economically sustainable cornerstone of modern food manufacturing.

Author contributions

P Geetha: Supervision; review & editing, Kalaivani Sundaravadivelu: conceptualization; visualization; writing. Pavithra S, Divakar P, Suriyasri Palani, Pugazhendhi Mohan, Jothy Lakshmy R.: data curation, methodology, validation; writing – original draft.

Conflict of interest

The authors declare no conflict of interest.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Acknowledgement

The authors would like to thank the teaching and non-teaching staff of the Department of Food Processing Technology, College of Food and Dairy Technology, for their extensive technical support and assistance.

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