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Review Article

Radio frequency food processing. Current status and perspectives – a review

Stefan Dragoev[1], Nikolay Kolev[1]✉*, Desislava Vlahova-Vangelova[1], Dessislav Balev[1]

[1] *Department of Meat and Fish Technology, Technological Faculty, University of Food Technologies, Plovdiv, Bulgaria*

Abstract
The present review provides a critical overview of the current status and prospects for the development and application of radio frequency food processing. The mechanism of action of radio frequency treatment, the dielectric properties of foods, the mechanisms for inactivating microorganisms and endogenous enzyme systems, the sensory and physicochemical changes occurring in radio frequency treated foods, as well as the application of radio frequency treatment in the food industry are discussed. Radio frequency processing technology has been found to have some advantages over conventional heat exchange systems in terms of time savings, higher profitability and better efficiency. In the available literature, the conducting of additional studies regarding the package violation and its permeability and integrity during radio frequency processing were discussed. Radio frequency heating has been shown to effectively eliminate pathogens and preserve better, physicochemical and sensory properties of food products compared to conventional heating due to shorter processing time. It is concluded that radio frequency energy heating is suitable for processing packaged foods that remain safe and stable during storage. For these reasons, it is concluded that radio frequency food processing has a very bright future.

Keywords
radio frequency, heating, treatment; processed food, quality, safety

Abbreviations
LOX – lipoxygenase; PPO – polyphenol oxidase; RF – radio frequency

✉*Corresponding author: Assis. Prof. Nikolay Kolev, PhD, Department of Meat and Fish Technology, Technological Faculty, University of Food Technologies, Plovdiv, Bulgaria; E-mail: n_kolev@uft-plovdiv.bg*

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Introduction

Innovative technologies for processing conventional foods and the factors affecting their acceptance are crucial for successful commercialization (Priyadarshini et al. 2019).

Radio frequency (RF) processing technology, based on dielectric heating, aims to rapidly heat foods using electromagnetic waves with frequencies ranging from 3 to 300 MHz (Kou et al. 2018). Volumetric RF heating is one of the key advantages of this technology, providing faster heating compared to traditional heat treatment methods (Zhang et al. 2021b).

In recent years, food processing using RF heating has significantly increased due to its advantages, including greater penetration depth, improved efficiency, and faster processing of food products (Bedane et al. 2021).

The energy absorbed by foods during RF heating depends on their dielectric properties, dimensions, volume, and orientation in the RF chamber (Marra et al. 2009). These factors influence heating uniformity (Bedane et al. 2021; Zhang et al. 2021b).

Higher temperatures during RF heating can lead to unexpected burning, especially on the food's surface, potentially affecting the organoleptic properties and quality.

To enhance heating uniformity during RF treatment, several suggestions have been proposed, such as combining hot air treatment with RF heating, mixing the sample in the RF chamber, modifying the shape of the electrodes, or adjusting the food's position during RF processing (Zhang et al. 2021b).

RF heating is considered an alternative to conventional heat pasteurization for various food products, such as goat milk (Zhu et al. 2014a,b), liquid egg melange (Zhu et al. 2021), fruit juices (Zhu et al. 2012), yogurt (Siefarth et al. 2014a,b), kiwi puree (Lyu et al. 2018) or conventional sterilization in cow's milk (Di Rosa et al. 2018). In all these cases, RF heating shortens processing time and minimizes food product deterioration.

RF treatment uses lower frequencies than microwaves, enabling deeper penetration, making it suitable for food materials with larger size and volume. Additionally, RF processing has the ability to dynamically control the moisture content of the final product. Oscillator circuits can be dynamically matched to load automatically, thereby controlling the power absorbed by the load (Mc Hugh 2016).

Mechanism of action of radio frequency treatment

RF energy is generated by a triode valve and applied to the food via a pair of electrodes. In the parallel plate RF system shown in Fig. 1, one of the electrodes is grounded to create a capacitor, storing electrical energy (Marra et al. 2009). RF waves generate heat in dielectric materials through bipolar polarization and/or ionic conduction (Fig. 1).

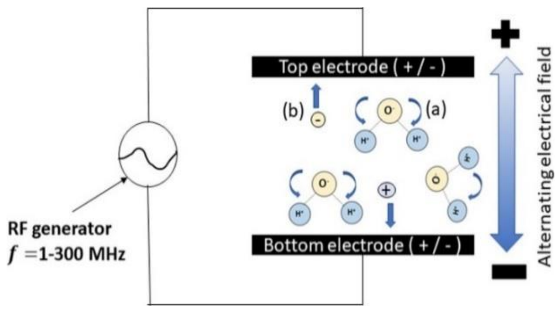

Figure 1. RF treatment diagram and heating mechanism for: (a) bipolar polarization; (b) ionic conductivity. Adapted from Guo et al. (2019) Copyright 2019, Springer Nature

Bipolar polarization. In bipolar polarization, water molecules and polar food product molecules can be polarized in the electromagnetic field, while other molecules become induced dipoles associated with the electric field voltage. Bipolar polarization is directly affected by molecular mass and electromagnetic frequency factors. Materials with smaller molecular weights are less active at the frequencies used for radiofrequency treatment (Jiang et al. 2020).

Ionic conductivity. Positively and negatively charged ions exhibit ionic conductivity as a result of relative polarization shifts between them. The alternating electric field moves these charged ions in a direction opposite to their polarity (Di Rosa et al. 2019). Ultimately, the electrically charged ions collide with the water dipoles.

As a result of the polarity change, the acceleration of the ions is reversed. These phenomena occur a million times per second depending on the frequency of the electric field. In this way, strong collisions can be caused that convert frictional energy into heat (Jiang et al. 2020). In other words, when the RF generator oscillates, the food products are exposed to the electromagnetic waves in the RF chamber. In this condition, migration of polar molecules and ionic components in the food product is observed, which transforms electromagnetic energy into thermal energy (Zhang et al. 2021b).

RF heating can be applied at three specific frequencies (Jiang et al. 2020; Zhang et al. 2020a), as follows:

- for industrial purposes - 13.56 MHz;
- for scientific purposes - 27.12 MHz;
- for medical purposes - 40.68 MHz.

Dielectric properties of radio frequency processed foods

Most foodstuffs are known to be dielectrics. The dielectric properties of some foods subjected to RF processing are presented in Table 1.

RF processing of foodstuffs is significantly affected by their dielectric properties (Zhang et al. 2021b). Dielectric properties are intrinsic characteristics of specific food materials that describe the degree of interaction between the material and the alternating electric field. They quantify the capacity of any food to store, reflect, and transmit electromagnetic energy (Jiao et al. 2018).

For this purpose, the dielectric constant of the food product ε can be calculated by equation (1) (Ryynänen 1995):

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

where:

ε - relative complex dielectric permittivity;

ε' - relative real dielectric permittivity (dielectric constant).

ε' - ability of the material of the food product to store electromagnetic energy;

j - equal to $\sqrt{-1}$ (imaginary unit);

ε'' - a coefficient reflecting relative dielectric losses.

The electric field of a propagating wave is affected by the dielectric constant ε', leading to changes in the wave impedance (the ratio between the electric and magnetic field strength).

The ability of the material of the food product to dissipate electromagnetic energy into heat is expressed by ε'', which is always positive and usually much smaller than ε' (Ryynänen 1995; Jiao et al. 2018).

Various factors, such as the chemical composition of food, moisture content of food, temperature, density, and frequency of the electromagnetic field, affect the dielectric properties of foodstuffs (Jiao et al. 2018; Zhang et al. 2021b). The main factor that has the strongest influence on the dielectric properties of food materials is moisture content (Jiang et al. 2020).

In this sense, the rate of RF-heated food products can be expressed by the power equation (2) (Ryynänen 1995):

$$Pv = 2\,\pi\, f\, \varepsilon_0\, \varepsilon''|E|^2 \qquad (2)$$

where:

Pv - energy developed per unit volume, W.m^{-3};

f - frequency of the electric field, Hz;

ε_0 - dielectric permittivity of the vacuum in the food, which is equal to 8.854×10^{-12}, F.m^{-1};

$|E|$ - electric field intensity, V.m^{-1};

The penetration depth (dp) of RF power is defined as the depth at which the incident power is reduced to 1/e (e = 2.7183) ≈ 37% of its value at the surface of the material.

dp in food products suffers losses and is often used to evaluate the uniformity of heating, as it can be calculated by formula (Zhu et al. 2012):

$$dp = c: 2\pi f 2\varepsilon' [\sqrt{1}+(\varepsilon''/\varepsilon')^2 - 1] \qquad (3)$$

where:

dp - penetration depth, m;

c - speed of light in free space (3×10^8 m.s^{-1}).

dp of electromagnetic waves in the food material is inversely proportional to the frequency of the electromagnetic field. Higher ε' and ε'' lead to a decrease in dp. Ştefănoiu et al. (2016) state that numerous experiments have been conducted to demonstrate the benefits of dielectric heating in terms of reducing:

Table 1. Dielectric properties of different foods subjected to radio frequency heating
*Adapted from Guo et al. (2019) Copyright 2019, Springer Nature

Type of food	Frequency, MHz	Established regression equations	R^2	Source
Liquid egg white	27.00 40.00	$\varepsilon' = 91.33 - 0.59T + 0.0081T2$ $\varepsilon'' = 482.46 - 3.96T + 0.11T2$ $\varepsilon' = 84.08 - 0.56T + 0.0057T2$ $\varepsilon'' = 239.96 + 0.11T + 0.0514T2$	0.930 0.970 0.800 0.980	Wang et al. (2009)
Raw cow's milk	27.12 40.68	$\varepsilon' = 95.409 - 1.339T + 0.0076T2$ $\varepsilon'' = 290.47 - 2.103T + 0.0274T2$ $\varepsilon' = 93.388 - 1.363T + 0.0079T2$ $\varepsilon'' = 202.56 - 1.421T + 0.0188T2$	0.995 0.965 0.995 0.967	Zhu et al. (2014b)
Raw goat's milk	27.12 40.68	$\varepsilon' = 116.71 - 2.122T + 0.0133T2$ $\varepsilon'' = 455.09 - 4.811T + 0.0292T2$ $\varepsilon' = 114.02 - 2.082T + 0.0129T2$ $\varepsilon'' = 320.75 - 3.439T + 0.0212T2$	0.997 0.995 0.998 0.995	Zhu et al. (2014b)
Raw cow's milk	40.68	$\varepsilon' = 127.6 - 1.034P - 3.598T - 0.02815PT$ $+ 0.4284P2 + 0.05067T2 - 0.001147P2\ T +$ $0.000332PT2 - 0.02303P3 - 0.0003228T3$ $\varepsilon'' = 245.7 - 1.712P - 4.479T + 0.04686PT +$ $1.368P2 + 0.08875T2 - 0.001966P2\ T -$ $0.0006614PT2 - 0.07358P3 - 0.0004875T3$	> 0.985	Zhu et al. (2015)
Apple juice	27.12 40.68	$\varepsilon' = -0.213T + 86.84$ $\varepsilon'' = 2.9925T + 62.199$ $\varepsilon' = -0.253T + 85.80$ $\varepsilon'' = 1.9481T + 40.971$	0.997 0.993 0.998 0.994	Zhu et al. (2012)
Pear juice	27.12 40.68	$\varepsilon' = -0.302T + 87.42$ $\varepsilon'' = 4.1099T + 78.963$ $\varepsilon' = -0.317T + 86.51$ $\varepsilon'' = 2.6755T + 51.807$	0.989 0.996 0.988 0.996	Zhu et al. (2012)
Orange juice	27.12 40.68	$\varepsilon' = -0.303T + 91.03$ $\varepsilon'' = 4.8774T + 106.32$ $\varepsilon' = -0.347T + 89.75$ $\varepsilon'' = 3.1693T + 69.702$	0.980 0.998 0.986 0.998	Zhu et al. (2012)
Grape juice	27.12 40.68	$\varepsilon' = -0.206T + 86.18$ $\varepsilon'' = 4.8496T + 86.309$ $\varepsilon' = -0.256T + 85.26$ $\varepsilon'' = 3.1591T + 56.635$	0.992 0.988 0.994 0.988	Zhu et al. (2012)
Pineapple juice	27.12 40.68	$\varepsilon' = -0.329T + 93.05$ $\varepsilon'' = 4.9732T + 158.74$ $\varepsilon' = -0.387 + 90.74$ $\varepsilon'' = 3.2397T + 103.79$	0.990 0.998 0.993 0.998	Zhu et al. (2012)

T is temperature, ℃; P is protein content, % w.b., $3.21\% \leq P \leq 7.12\%$

- microbial contamination of food;
- elimination of pests other than pathogenic and putrefactive microflora (which represent another type of biological hazard) and
- the ability to heat the product without significant undesirable changes occurring in it.

Only three frequencies are authorized for use in the USA: 13.56 MHz, 27.12 MHz, and 40.68 MHz. When designing RF systems and process equipment, the physical characteristics that affect the heating of food must be taken into account, including its dielectric properties, shape, dimensions, volume, and position of the product (Marra et al. 2009).

Foods contain polar molecules such as water. Water molecules have dipole moments, positively and negatively charged centres that do not match. When food is placed in an electric field, the polar molecules line up in the direction of the field, following the dipole moment phenomenon. Thus, the polar molecules continuously rotate to align with the field as the field alternates. Friction is created between the molecules, converting electromagnetic energy into heat. The latter increases the temperature of the food.

The dielectric properties of food materials are affected by temperature, moisture content, composition, and mineral content (Routray and Orsat 2018). Dielectric properties are related to titratable acidity, ionic content, and pH value (Routray and Orsat 2018). The main parameters determining the coupling and distribution of electromagnetic energy during dielectric heating of foods are their dielectric properties (Wang et al. 2003). The uniformity of RF heating is a result of the material's dielectric properties, along with other thermal properties of food and process equipment (Routray and Orsat 2018). Dielectric properties can be useful for quality control in food processing, such as the online monitoring of the yogurt fermentation process (Guo et al. 2018) or the estimation of the protein content of raw cow's milk (Zhu et al. 2015). Various studies have been conducted to measure the dielectric properties of foods. In Table 1, equations for predicting the dielectric properties at different temperatures of fruit juices, cow and goat milk, liquid egg melange, and albumen subjected to RF treatment are presented.

Evaluation of the dielectric properties in the RF range of fruit juice and raw milk shows that ε' decreases with increasing frequency, and the temperature rise at a given frequency ε' decreases. ε'' decreases with increasing frequency in the RF range, but the effect of increasing temperature depends on the type of product. In cow's milk and fruit juices (from apple, pear, oranges, grapes, and pineapple), ε'' increases with increasing temperature, but in goat milk, ε'' decreases (Zhu et al. 2012, 2014b).

As the temperature increases, the decrease in ε' leads to a decrease in the static dielectric constant due to the enhancement of the Brownian motion of the molecules. In industrial dielectric heating, ionic conduction and dipole relaxation are dominant loss mechanisms observed. However, ionic conduction is the dominant loss mechanism at lower frequencies (Zhu et al. 2012). In liquid egg melange, white, and yolk, ε' and ε'' are found to decrease with increasing frequency and increase with increasing temperature at 27 and 40 MHz; ε' and ε'' of liquid egg melange are smaller than liquid egg white (Wang et al., 2009). Therefore, the origin and composition of the food affect the dielectric properties. Wang et al. (2008) noted that as the fat content of raw milk increased, both ε' and ε'' decreased. Guo et al. (2018) found that ε'' increases with increasing fermentation time and slightly decreases when the pH approaches a value around 4.4. For this reason, it is crucial to know the dielectric properties of foods undergoing RF heating to develop an efficient heat exchange process.

Jiao et al. (2014b) found that ε' and ε'' affect the heating rate at a fixed frequency and electrode gap. When the value of ε' and ε'' are close, the maximum heating rate can be achieved. Dielectric heating at 27 MHz is useful for bulk materials (Liu et al. 2020).

RF penetration depths for apple and grape juices decrease with increasing temperature. For example, at 40.68 MHz, the penetration depth of grape juice at 95°C is 45.6 mm, and at 15°C, it is 102.0 mm (Zhu et al. 2012).

To achieve effective pasteurization using dielectric heating, the thickness of the food should not exceed 2-3 times the penetration depth (Zhu et al. 2012; Liu et al. 2020). If a small penetration depth is used, the penetration thickness of RF heating in juices will be about 140 mm at 27.12 MHz and 100 mm at 40.68 MHz (Zhu et al. 2012). The optimal pasteurization thickness of raw milk is achieved by heating at 27.12 MHz and will be about 130-195 mm, while at 40.68 MHz, it will be 110-165 mm (Zhu et al. 2014b). Dielectric properties can be used to estimate penetration depth and to determine product thickness in RF processing (Boreddy and Subbiah 2016).

Temperature distribution and heating uniformity of foods are the most critical issues affecting the microbiological safety of food products in RF pasteurization (Li et al. 2015). A significant problem for the development of the RF food pasteurization process is the non-uniform heating (Jiao et al. 2014a) caused by the non-uniform distribution of the electromagnetic field in the material and the surrounding space, especially for materials with high moisture content (Zhu et al. 2017; Guo et al. 2019). Increased moisture content and increased food thickness lead to a decrease in heating uniformity (Li et al. 2015). The heating behaviour of RF-assisted heat processing of foodstuffs depends on the proximate composition of the food, the geometry, and the orientation of the load in the RF chamber (Bedane et al. 2021). The RF power level also plays a significant role in heating uniformity. The lower power used results in a slower heating rate and less uniform temperature distribution in food systems with different geometries (Bedane et al. 2021). The heating rate of RF-treated foods depends on the anode and network current, dielectric properties, and the surrounding environment. The RF power applied to the product increases as the electrode gap decreases, resulting in a linear increase in the heating rate (Awuah et al. 2005; Rincón and Singh 2016), but the likelihood of curling and melting of the package also increases (Rincón and Singh 2016).

Jiao et al. (2014b) found that when RF heating is applied to saltwater, if the values of ε' and ε'' are close to each other, the maximum heating rate can be achieved at a fixed electrode gap and material thickness. Zhu et al. (2021) observed that the mean temperature of liquid egg melange, white, and yolk during RF heating increased almost linearly with treatment time for all electrode gap sizes tested, and the heating rate of liquid egg yolk was higher than observed in liquid egg melange and egg white. Furthermore, the rate of RF heating of the liquid egg melange is inversely proportional to the size of the electrode gap. Therefore, RF heating offers a much higher heating rate and better pasteurization efficiency (compared to conventional pasteurization). Thus, RF heating has excellent potential as a pasteurization method for liquid egg products.

In foodstuffs, non-uniform RF heating, especially edge reheating, is a major obstacle to the application of RF pasteurization (Zhang et al. 2020a). Various ways to improve uniformity during heating of food products have been proposed. (Jiao et al. 2014a; Zhang et al. 2017, 2020a). Some suggestions include adjusting the output power, reducing the heating rate, changing the size or position, modifying the electrode, using hot air, moving and mixing, layering, using a similar dielectric material around the samples, placing mica plates on top of the sample with polypropylene blocks placed in between the samples, and placing rectangular polyetherimide plates above and below the sample container (Ling et al. 2018; Guo et al. 2019). These methods are limited to solid foods. The non-uniform heating is due to contact heating between particles or between the particle and pan and the effect of focusing heating at the corner/edge (Huang et al. 2018).

Studies evaluating temperature distribution or heating uniformity in liquid foods have found that the centre temperature of kiwi puree is the highest, followed by kiwi puree around the sides of the glass package, and the surface temperature is the lowest. The temperature difference between the core and surface patches is approximately 6°C (Lyu et al. 2018).

Siefarth et al. (2014a) applied radiofrequency heating to post-fermentation yogurt and found homogeneous heating of yogurt processed in a radiofrequency-heated water bath at 58 and 65°C. In contrast, at 72°C, yogurt showed significant superheating, followed by severe curd shrinkage and whey separation. Siefarth et al. (2014a) explained this phenomenon by the abrupt change in the dielectric properties of yogurt above 70°C, which provokes faster heating. Dissociated ions in foods also produce heat through ionic conduction. With it, the ions oscillate back and forth in the food, creating friction and heat.

Electromagnetic characteristics of foods are important when the process parameters have to be determined. Two more important technological properties of RF processed foods are their permeability and penetrability (Mc Hugh 2016). Permeability has very little effect on dielectric heating and is usually neglected. The penetrability of foods is a parameter most often used to describe their dielectric properties. It relates to the reflection of electromagnetic waves at interfaces and the attenuation of wave energy in food (Mc Hugh 2016).

The conclusion was made that the three most popular methods for measuring the dielectric properties of foods are:

- ❖ the transmission line method;
- ❖ the open-ended coaxial probe method and
- ❖ the resonant cavity method.

Mechanisms of inactivation of micro-organisms by radio frequency heating

RF heating can be applied to eliminate microorganisms (pathogenic and putrefactive) and to reduce the loss of food quality characteristics (Jiao et al. 2014a). The mechanism for microbial inactivation during dielectric heating is mainly due to thermal effects. RF heating inactivates microbes by conventional thermal mechanisms, including thermally irreversible denaturation of enzymes, proteins, and nucleic acids. Enzymes catalyze the biochemical reactions occurring in the living cell of the microorganism. When they are subjected to high temperatures, they lose their active centres, disrupting several basic biochemical mechanisms necessary for the survival of microorganisms.

Nucleic acids such as DNA (deoxyribonucleic acid) are essential for the replication and vegetative propagation of microorganisms. At high temperatures, nucleic acids are also denatured because double-stranded DNA becomes single-stranded due to breaking of hydrogen bonds between the bases forming the strands (Dev et al. 2012). RF decontamination of fungi in foodstuffs is believed to be due to thermal disruption and degradation of DNA, proteins, and lipids, resulting in cell rupture (Akhila et al. 2021).

Heat treatment is an effective method for inactivating foodborne viruses as well (Shahi et al. 2021). Inactivation of viruses by heat occurs by inhibiting host cell recognition/binding, as heat induces structural changes in viral proteins (Wigginton et al. 2012).

Factors affecting the thermal resistance of microorganisms in radio frequency-heated foods include water activity, proximate composition, pH of the heating medium, growth temperature, microbial strain, growth stage, and are mainly influenced by the final temperature, heating rate, and holding time (Huertas et al. 2016; Kou et al. 2016; Zhang et al. 2021b). Therefore, the rate of RF heating can directly affect microbial survival and food quality (Zhu et al. 2017).

Thermal inactivation of pathogenic strains depends on microorganism-related factors (strain, initial population, growth phase/state, etc.), process-related factors (heating temperature, holding time, environmental conditions, etc.), and factors related to the product (chemical composition, physical properties, moisture content, pH value, and many others) (Cheng et al. 2021). A non-isothermal step is observed in RF heating, which can affect the rate of inactivation of microorganisms such as pathogens (Zhang et al. 2020a). The effect of RF heating on the microbiological status of some foods is summarized in Table 2.

Our own experiments prove that RF treatment of fried meatballs packaged under modified atmosphere can successfully eliminate the presence of pathogens *Listeria monocytogenes* and *Salmonella spp*. during 90 d of storage at 2 - 6°C.

Awuah et al. (2005) found that RF heating could inactivate *Listeria innocua* and *Escherichia coli* in milk under continuous flow conditions. For 55.5 seconds of total residence time, up to 5- and 7-log reductions were found during heating of milk inoculated with *Listeria innocua* and *Escherichia coli* K-12, respectively, at 1200 W and a temperature of approximately 65°C in the applicator outlet tube.

Rincón and Singh (2016) have established what is the effect of RF heating (27.12 MHz, 6 kW) on the resistance of *Escherichia coli* strains in phosphate buffered saline packed samples.

Table 2. Effects of radio frequency heating on the microbiological status of liquid foods
* Some of data are adapted by Lyu et al. (2018) Copyright 2017, John Wiley and Sons

Product	Radio frequency treatment, RFt	System/Process mode	Microorganisms	Log reduction or log CFU.g^{-1}	Source
Fried meat balls packed under MAP	7 kW, 27.12 MHz Total dwell time: between 10 and 30 min A specified voltage between the electrodes 2000 – 4000 V Initial temperature: 5.7 – 10.8°C Final temperature: 7.5-14.2°C.	Radio frequency equipment, Model "RF 1 × 7 kW", Series 2627/1 (Stalam Co., Nove, Italy)	*Listeria monocytogenes* *Salmonella spp.*	Not found (n=5; c=0) in 25 g	own data
Liquid egg yolk (LEY)	1.2 kW, 27.12 MHz Total dwell time: 55s (29.5 and 26 s in applicator and holding tube respectively) Final temperature: 65°C. Heating rate: 1.48-2.20°C.s^{-1}	50-Ω system/ Continuous mode (270 -304 mL.min^{-1})	*Listeria innocua* *Escherichia coli*	5 log reduction 7 log reduction	Awuah et al. (2005)
Liquid egg white (LEW)	2.21 kW, 27.12 MHz Total residence time: 6.9 s Final temperatures: 75-125°C A plate heat exchanger was used to preheat the LEW before the radio frequency heater.	Not specified/ Continuous mode	Total count of mesophilic microorganisms	Radiofrequency heated milk at 75°C: 180 CFU.mL^{-1} at 80°C: 530 CFU.mL^{-1} at 85°C: 47 CFU.mL^{-1} at 90°C: 14 CFU.mL^{-1} at 95°C: 25 CFU.mL^{-1} at 100 °C: 9 CFU.mL^{-1} at 105°C: 4 CFU.mL^{-1} at 105-125°C: < 1 CFU.mL^{-1}	Di Rosa et al. (2018)
Liquid egg melange (LWE)	12 kW, 27.12 MHz Electrode gap size: 115 mm, 120 mm and 125 mm, for LWE and LEW; 120 mm, 125 mm, 130 mm for LEY Treatment time: 160-260 s (LWE), 150-318 s (LEW), 80-260 s (LEY)	Free running oscillatory system/ Batch mode (40 mL)	*Salmonella enterica serovar Enteritidis*	In LWE, a 5.62 log reduction was achieved by RF treatment in 220 s at an electrode gap size of 120 mm. In LEW, a 4.36 log reduction was achieved after 285 s at 125 mm. In LEY, a 5.31 log reduction was achieved after 180 s at 125 mm.	Zhu et al. (2021)
Raw cow's milk	6 kW, 27.12 MHz Electrode gap size: 9 cm Final temperature: 65°C	Free running oscillator/ Batch mode (5 mL)	*Escherichia coli* *Staphylococcus aureus*	They are not detected 5.65 log reduction	Kou et al. (2016)
Yoghurt	16 kW, 27.12 MHz Initial temperature of yogurt: 40°C. Treatment time: 60 s (58°C), 90 s (65°C), 120 s (72°C). Retention time: 60 s Heating rate: 0.28 ± 0.02 K.s^{-1}	Radio frequency water bath/ Party mode	Lactic acid bacteria (LAB) / count of molds and yeasts (YMC)	Destruction of yeasts and molds. LAB partially survive RF heating at 58 and 65°C while inactivated by conventional treatment	Siefarth et al. (2014a)
Kiwi puree	10 kW, 27.12 MHz Electrode gap size 105 mm. Treatment time 210 s. Initial mash temperature: 20°C. Heating rate ~0.2 ± 0.1 K.sa^{-1}	Free running oscillatory system/ Party mode	Total Aerobic Bacterial Count (TAC)/Mold and Yeast Count (YMC)	TAC reduction: 4.81 log CFU.mL^{-1} YMC reduction: 2.62 log CFU.mL^{-1}	Lyu et al. (2018)

Kou et al. (2018) subjected apple juice inoculated with *Escherichia coli* and *Streptococcus aureus* to RF heating (27.12 MHz, 6 kW), obtaining 5.38 log CFU.mL^{-1}.

Liu et al. (2018a) reported that RF heating inactivated microbes in kiwifruit puree, resulting in a reduction of 4.81 log CFU.mL^{-1} in total aerobic bacterial counts and 2.62 CFU.mL^{-1} in yeast and mold counts. These reductions were comparable to those achieved with traditional heat pasteurization.

Zhu et al. (2021) applied RF heating to liquid egg products artificially contaminated with *Salmonella enterica*. They found a 5.62 log reduction in liquid egg mélange (RF heated for 220 s at 120 mm), a 4.36 log reduction in liquid egg white (RF heated for 285 s at 125 mm), and a 5.31 log reduction in liquid egg yolk (RF heated for 180 s at 125 mm), showing less processing time and greater log reduction compared to conventional processing.

Di Rosa et al. (2018) sterilized raw bovine milk using a combination of steam and RF heating. They found different total numbers of mesophilic microorganisms at different final temperatures and observed that at temperatures higher than 85°C, the sterilization achieved was comparable to that of UHT milk.

Finally, Siefarth et al. (2014a) evaluated the effect of RF heating on lactic acid bacteria, molds, and yeasts in stirred acid gel after cultivation. They found that RF heating and conventional pasteurization inactivated yeasts, molds, and lactic acid bacteria, but these beneficial microorganisms were still present (in reduced numbers) after RF heating at 58 and 65°C, demonstrating the mildness of the RF treatment. Similar studies have shown that RF heating can inactivate spoilage and pathogenic microorganisms in processed liquid foods.

The thermal tolerance of bacteria is significantly affected by the rate of heating. A slow heating rate often results in increased thermostability of bacteria with a longer D-value at the same target temperature (Kou et al. 2016). Kinetics of inactivation of pathogenic bacteria in liquid food matrices under non-isothermal heating demonstrated that lower heating rates increase the thermo-resistance of pathogens (Hassani et al. 2005; Huertas et al. 2016). Research on thermal resistance of pathogens such as *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella spp*. in milk, fruit juices, and liquid egg products shows that resistance to heat depends on various factors (Chhabra et al. 1999; Doyle and Mazzota 2000; Mazzota 2001) such as pH, processing temperature, proximate composition (fat, content of soluble solids, organic acids, etc.), type of microorganism, strain, culture condition before the experiment, presence of other microorganisms, heat source, and recovery conditions (Usaga et al. 2014; Pagal and Gabriel 2020).

Inactivation of endogenous enzyme systems by radio frequency heating

Enzymatic browning, which is induced by polyphenol oxidase, is a common color change in plant-derived foods. When polyphenol oxidase reacts with phenolic substrates, it oxidizes them to dark o-quinones, leading to a reduction in the sensory and nutritional qualities of fruits and vegetables. RF blanching of fruits and vegetables has been shown to effectively inactivate enzymes, including polyphenol oxidase, which improves product quality, reduces browning reactions, and helps maintain nutrient content (Zhang et al. 2020b).

For instance, Tian et al. (2018) conducted a study on apple tissue subjected to RF heating (3.5 kW/27.12 MHz, 35 mm between electrodes) for 10 minutes. They found that this treatment effectively inactivated polyphenol oxidase and maintained a higher quality of squeezed apple juice compared to fresh squeezed juice. Additionally, Zhang et al. (2020b) investigated the effect of RF-assisted blanching on polyphenol oxidase activity in potatoes and observed only 1.35% residual polyphenol oxidase activity at 90℃. This indicates that RF heating causes structural changes in the enzyme protein, such as a reduction in α-helix content in the secondary structure of polyphenol oxidase.

Peroxidase is another enzyme involved in the browning reaction of fruits and vegetables, and it catalyzes the oxidation and polymerization of phenols using H_2O_2 produced by polyphenol oxidase oxidation of phenols (Zhang et al. 2021a). Yao et al. (2021) studied the inactivation of peroxidase in steamed lettuce using RF heating (6 kW/27.12 MHz, free-running RF system). They observed that peroxidase inactivation was significantly affected by the RF heating rate, with higher inactivation efficiency achieved by decreasing the electrode gap. Interestingly, peroxidase consists of two isoenzymes, including heat-resistant and heat-labile fractions. The heat-resistant fraction can only be deactivated when the center temperature reaches more than 85℃, while the heat-labile fraction is inhibited at lower temperatures.

Lipoxygenase, abundant in the seeds of grain legumes and potato tubers, is associated with off-tastes, odors, and discoloration in foods due to the oxygenation of polyunsaturated fatty acids (PUFAs) to form fatty acid hydroperoxides (Baysal and Demirdöven 2007). RF heating has been found to thermally inactivate lipoxygenase at temperatures above 60℃, contributing to the preservation of essential fatty acids and prolonging the shelf life of foods (Baysal and Demirdöven 2007).

In summary, RF heating has been shown to be effective in inactivating enzymes such as polyphenol oxidase, peroxidase, and lipoxygenase, contributing to the maintenance of food quality, preservation of nutrients, and reduction of off-flavors and off-odors. The degree of enzyme inactivation may vary depending on factors such as the water content of the food, the heating rate, and the final temperature. Additionally, RF heating offers the potential for producing high-quality processed foods with attractive sensory properties, but careful control of heating parameters is essential to avoid uneven heating and quality loss.

Sensory and physicochemical changes in radio frequency processed foods

RF technology has been studied to produce high-quality processed foods that maintain high quality, good appearance, mouthfeel, and attractive sensory properties (Rattan and Ramaswamy 2014). RF heating enables better quality control of fresh foods (Guo et al. 2019). Furthermore, RF heating can be beneficial when applied to packaged foods (Wang et al. 2003). However, strong uneven heating can lead to quality loss (Jiao et al. 2014a).

Radiofrequency heating is applied in the processing of various foods for various purposes, such as pasteurization, sterilization, blanching, or extending the shelf life, using batch or continuous mode. The effects of radiofrequency heating on the organoleptic properties of food treated with radiofrequency heating are summarized in Table. 3. In the Table 4 presents results regarding the influence of RF heating on the physicochemical properties of various foods.

Lyu et al. (2018) found that RF heating allows extremely low temperature and less processing time, preserving the properties of kiwi puree. RF heating better preserves vitamin C, total phenolic compounds, antioxidant capacity and retains better color than conventional during storage.

Siefarth et al. (2014a) applied radiofrequency heating to yogurt at different temperatures (58, 65 and 75℃) and found that 72℃ caused overheating, which negatively affected its quality.

However, the RF-treated yogurt at 58 and 65℃ did not show significant changes in its pH and organoleptic properties. Slight color changes are observed after heat treatment.

Siefarth et al. (2014b) found that post-fermentative RF heat treatment produced yogurt with a more similar microstructure and consistency to stirred reference yogurt compared to conventional treatment during 4-week storage (8 ± 1°C). However, RF treatment provokes the development of white flakes and a decrease in gel strength. These defects are reversible with an additional homogenization step after heat treatment. Siefarth et al. (2014a, b) also developed a rapid, homogeneous and gentle RF treatment up to 65℃, extending the shelf life of yogurt by reducing the number of microorganisms, while observing only minor sensory and reversible changes in milk consistency.

Zhu et al. (2021) treated liquid egg products with radiofrequency heating and found that color change, emulsification and foaming of liquid egg products were not affected after treatment with the optimal RF pasteurization protocol. RF-treated liquid egg products were similar to conventionally pasteurized samples. However, coagulation of egg whites is observed if the temperature exceeds 67℃ in liquid egg yolk or 60℃ in liquid egg white. The latter is more sensitive to temperature than other egg products, so when the temperature exceeds 60℃, the protein coagulates.

Table 3. Effects of radio frequency heating on the organoleptic properties of foods

Target	Product	Storage time	Main effect on sensory properties	Source
Enzyme inactivation	Apple juice	Not specified	The panellists indicated that the taste of the 10-min radiofrequency-treated sample was close to the taste of freshly squeezed apple juice. The result of the radiofrequency treated sample was higher than that of the conventionally treated samples	Tian et al. (2018)
Post-fermentation heat treatment	Yoghurt	5 weeks at 8°C	Taste and odor profiles are similar to the reference product. Applying a triangle test, the panel's trained tasters found no difference between the reference yogurt and the radiofrequency-treated sample at 65°C	Siefarth et al. (2014a)
Pasteurization	Kiwi puree	7 weeks at 4°C	Consumers preferred radiofrequency-treated kiwifruit puree to conventionally treated samples in terms of overall appearance, color, aroma, and taste	Lyu et al. (2018)
Sterilization	Raw cow's milk	40-45 days at 4°C	Appearance and taste evaluation, performed through an innovative combination of electronic sensing and data synthesis, revealed that the organoleptic properties of milk were preserved or minimally modified by RF heating	Di Rosa et al. (2018)
Extending the shelf life	Fried meatballs under MAP	90 days at 2 - 6°C	RF processing ensures the production of high-quality fried meatballs packaged under MAP (70%N_2/30%CO_2) that maintain attractive sensory properties such as appearance, taste, smell and consistency during their 60-d storage at 2 to 6°C. The sensory properties of the product harmonize with the results of the instrumentally recorded color characteristics, oxidative changes and microbiological status of the product.	own data

Di Rosa et al. (2018) applied RF heating to raw bovine milk at different final temperatures and found that the taste and appearance of the milk were preserved or minimally modified. Physicochemical properties (lipids, proteins, lactose, pH and acidity) for raw and RF-heated milk were similar, indicating that RF heating does not affect milk proximate composition even at high temperatures.

In addition, the sensory properties of RF heated milk are similar to raw milk. Therefore, RF heating may be a suitable process for the production of safe milk with a long cold chain distribution shelf life of 40 - 45 days.

Our unpublished to this moment data shows that RF treatment for 28 min at ≈ 2100 V of fried meatballs packed under a modified atmosphere (70%N_2/ 30%CO_2) allow the product to be stored at 2 - 6℃ for 60 d without significant negative effects impact on its quality and safety. After the 60th day of cold storage, protein carbonyls were found = 0.185594 nmol DNPH.g^{-1} protein; 2-thiobarbituric value = 1.56464 mg MDA.kg^{-1} and total aerobic microorganism colony count (TPC) approx. 56 CFU.g^{-1}. The tryptophan content (Try) is 3.54177 mg.100g^{-1}, and the red/yellow color component ratio on the cut surface (Ra*/b*) = 0.456017, and on the external surface (Ra*/b*) = 1.17994.

Applications of radio frequency processing in food industry

Fighting the causative agents of brown rot on stone fruit. RF treatment of fruit for 4.5 min, with fruit immersed in water at 40℃, was found to be very promising for the control of brown rot caused by *Monilinia* spp. on peaches and nectarines. In general, the time of infection and the level of fruit maturity did not have a significant effect on the efficacy of radiofrequency treatment and the incidence of brown rot was significantly reduced in peaches and nectarines inoculated 0, 24 or 48 h before treatment and at all levels of maturity. RF treatment significantly reduced brown rot incidence at all inoculum concentrations evaluated (10^3, 10^4, 10^5 и 10^6 conidiam L^{-1}). In naturally infected fruit, brown rot incidence was significantly reduced from 92% among control fruit to more as little as 26% in peaches, and complete control of brown rot is achieved in nectarines. RF treatment had no effect on fruit firmness and a delay in fruit softening was even observed. Furthermore, the external and internal appearance of the fruits was not affected by the treatment (Sisquella et al. 2014).

Inactivation of oxidative enzyme systems in apples and vegetables. The effect of increasing RF electric fields on the activity of oxidative enzymes has been studied in model systems and foods. RF treatment was found to effectively inactivate both enzymes, although PPO was more sensitive to increasing the RF electric field. The effectiveness of RF treatment is attributed to the generated thermal effect, while the contribution of the electromagnetic field is negligible (Manzocco et al. 2008). It was determined that the RF processing allows the apples to be adequately blanched. Puree obtained from RF-treated blanched apples was evaluated as comparable to conventionally blanched with water for color and other sensory properties. RF treatment allows complete inactivation of oxidative enzymes and can be successfully used at an industrial level for blanching vegetables instead of conventional treatment (Manzocco et al. 2008).

Disinsection of nuts and dried fruits. Insect infestation is a major safety problem for a number of foods. Chemical fumigants (such as methyl bromide) are commonly used for post-harvest pest control. Alternative heat treatments often lead to a deterioration in product quality. This is why RF processing allows fast and uniform heating of many substrates. A number of studies confirm that RF treatment is suitable for effective disinsection of nuts and dried fruits (Mc Hugh 2016).

Radio frequency assisted freezing of meat. The potential use of RF processing to aid in the freezing of foods has been explored. To this aim, freezing of pork was carried out in RF pilot equipment modified to allow immersion of food in liquid nitrogen spray. During freezing, pulsed RF treatments (RF-assisted cryogenic freezing) were applied. Freezing under cryogenic fluid flow (cryogenic freezing) and freezing in air were used as controls. The results have shown that RF-assisted freezing is possible using low voltage (2 kV) pulses. Thawing losses of RF cryogenically frozen meat were much lower than those observed during air thawing and cryogenically frozen meat, indicating similar drip losses. Analyzes performed on the microstructure of the meat showed that the tissue had a better cellular structure when RF treatment was used. Much less intercellular cavities and cell disruption were observed.

Table 4. Effect of radio frequency processing on the physicochemical properties of foods

Product	Primary effect on physical properties	Source
Raw cow's milk	Alkaline phosphatase and lactoperoxidase were inactivated in RF treated samples at 80 and 85°C. Physicochemical parameters of RF-treated milk (lipids, proteins, lactose, pH and acidity) were similar to raw milk, indicating that RF heating did not affect milk composition	Di Rosa et al. (2018)
Yoghurt	RF heating at 72°C results in superheating, followed by severe curd shrinkage and whey separation. RF-treated samples at 65 and 58°C did not show significant changes in pH. Slight color changes are observed after heat treatment. No souring was observed during storage of yogurt.	Siefarth et al. (2014a)
Kiwi puree	Better retention of vitamin C, total phenolic compounds, antioxidant capacity and color. The soluble solids content of the RF treated sample was higher than that of the control sample. The RF-treated sample showed a lower pH value and a higher titratable acidity than those of the control sample	Lyu et al. (2018)
Apple juice	The total soluble solids of the RF-treated samples were similar to those of the control sample. The pH values of the RF-treated samples were higher than those of the control sample. RF heating preserves total phenolic content better than conventional treatment. The color of the 10 min RF-treated samples was better than the conventionally treated ones. Fewer objectionable components are generated during RF heating	Tian et al. (2018)
Liquid egg products	RF heating does not result in a visible change in color, emulsification and foaming of liquid egg products. The quality of liquid egg products of conventional pasteurized and RF treated samples did not differ	Zhu et al. (2021)
Fried meatballs packed under modified atmosphere	After RF treatment for 28 min at ≈ 2100 V, the fried meatballs packed under a modified atmosphere (70%N_2/ 30%CO_2) can be stored at 2 - 6°C for 60 d without significant negative effects impact on the quality and safety. After the 60th d of cold storage, a minimum levels of protein carbonyls were found = 0.185594 nmol DNPH.g^{-1} protein; 2-thiobarbituric value = 1.56464 mg MDA.kg^{-1} and total aerobic microorganism colony count (TPC) approx. 56 CFU.g^{-1}. The tryptophan content (Try) is 3.54177 mg.100g^{-1}, and the red/yellow color component ratio on the cut surface (Ra*/b*) = 0.456017, and on the external surface (Ra*/b*) = 1.17994.	own data

Compared to the controls, the RF-frozen meat contained smaller ice crystals that were mainly located in the intracellular spaces. This is due to the ability of RF treatment to depress the freezing point, thereby producing more nucleation sites. The treatment allows controlling the size and distribution of ice crystals in tissues, possibly by favouring the torque of water molecules (Anese et al. 2012).

Thawing and tempering of frozen food products. Traditional methods of defrosting food suffer from inherent disadvantages such as slow heat transfer and large drip losses. The larger the size of the product, the longer it takes to defrost. This provides opportunities for the reproduction of various types of microorganisms incl. and of putrefactive and pathogenic bacteria, leads to large drip losses and causes adverse changes in meat quality, leading to significant economic losses (Mc Hugh 2016). During the RF defrosting / tempering of frozen foods, the increase in temperature with the phase change leads to a significant increase in the dielectric properties of the product. Llave and Erdogdu (2022) have found how influencing factors such as electrode position, sample geometry and size, electrode gap of the applied RF process, and charged electrode potential.

RF processing rapidly and voluminously generates heat and defrosting is achieved in minutes rather than hours or days, even for large product blocks. RF treatment can also be applied directly to packaged foods. The heating process leads to a significant reduction in the drip loss. It minimizes product deterioration and slows bacterial growth, making it suitable for defrosting (Mc Hugh 2016).

Radio frequency thermal treatment of pork followed by steam cooking. RF cooking is a volume heating technology that reduces the time it takes to cook food, but the heat is not evenly distributed. A two-step process of cooking pork legs in a RF tunnel and in a steam oven (RF-ST) was developed and compared with cooking in a steam oven only (ST). The temperature distribution was monitored during cooking and the accumulated microbial mortality was calculated. The combination of RF-assisted and steam cooking (RF-ST) allows to obtain a cooked ham similar to that obtained by conventional steam cooking (ST). RF-ST processing duration reduced by 50%. Slight differences were observed in the technological and sensory quality of the final product. To avoid product overheating problems during RF processing, the ends of the legs are shielded with aluminium foil or other suitable insulating material (Muñoz et al. 2020).

Radio frequency drying after baking of biscuits, crackers and cereal-based snacks. RF drying after baking is common in the production of cookies, crackers, cereals and snacks (Mc Hugh 2016). Surface cracks in these foods often occur during traditional drying processes due to the moisture gradient in the product. RF drying solves this problem because the energy penetrates evenly, minimizing moisture gradients. The use of RF drying eliminates fading and deterioration of flavor due to heat build-up. It allows to increase the speed of the production line (conveyor), to maintain more stable moisture levels, lower drying temperatures and smaller traces of the technological equipment left on the surface of the food (Mc Hugh 2016).

Anese et al. (2008) studied the effect of RF heating on acrylamide formation in bakery products. The results showed that when baking in a circulating air oven, the baking process assisted by radiofrequency heating (i.e., applying the RF heating in the final stages of the baking process) proved to be a promising strategy for keeping acrylamide levels low in bakery products. The best results were obtained for products that were moved from hot air baking to radio frequency heating when their residual moisture was still quite high (around 10%).

Radiofrequency pasteurization and sterilization of foods. Sterilization processes are usually carried out by treating products with drastic heat treatment, which leads to a deterioration in their quality. Pasteurization is a relatively "gentler" heat treatment carried out at temperatures below the boiling point of the water. Both traditional sterilization methods and pasteurization methods use saturated steam or hot water under pressure to heat packaged foods. The temperature rise of the product is slow and uneven, which often causes overheating of the outer layers of the food and leads to a deterioration of the quality of the food. The ability of RF processing to quickly and voluminously generate heat in the product minimizes degradation of product quality. RF pasteurization was used in the processing of canned meat. The application of a similar type of pasteurization in liquid foods and beverages is also being explored (Mc Hugh 2016).

Alternative radio frequency pasteurization of liquid foods. Radiofrequency heating can be used to pasteurize liquid food, to reduce the microbial population and to preserve the nutritional and physicochemical properties of the food (Soto-Reyes et al. 2022).

According to Rezaeimotlagh et al. (2021), RF treatment is an alternative to conventional heating in liquid foods, guaranteeing their microbial safety. Changing the electrode spacing can adjust the RF power in a specific load (Zhu et al. 2014a).

Zhu et al. (2021) determined the effect of radiofrequency heating on the microbiological safety of liquid egg products (egg melange, egg white and egg yolk) artificially inoculated with Salmonella enteritidis.

Awuah et al. (2005) proposed a continuous flow radiofrequency heater for milk processing. Milk flows in laminar flow through the Teflon tube (2.22 cm internal diameter and 76.20 cm long) placed between an aluminium electrode and a ground plate.

Conclusions

RF (Radio Frequency) processing technology has several advantages over conventional heat exchange systems in the food industry. It offers time-saving, higher profitability, and better efficiency in terms of food safety, under identical operating conditions. RF heating has been shown to effectively eliminate pathogenic and putrefactive microorganisms in food, while preserving the physicochemical and sensory properties as well as the nutritional value of foods due to its shorter processing time. Additionally, RF heating allows for heating the product inside its package, reducing the risk of cross-contamination and adhering to HACCP principles.

However, to apply RF heating in liquid pasteurization successfully, certain processing parameters need to be optimized. These include the scaling of RF heating, operating frequency, output power, electrode gap, target temperature, holding time, uniformity of heated food, and processing efficiency. Research is needed to determine the most suitable packaging materials and appropriate package size for specific food products to avoid package permeability and integrity issues.

The proximate composition of the food and the positioning of packages in the machine chamber can also influence the rate of heating during RF processing. To ensure the effectiveness of RF heating in extending the shelf life of foods, a "softer" heat treatment regime and well-chosen packaging materials are essential.

One common challenge in RF processing is avoiding dielectric breakdown and thermal hot spots. Researchers and process equipment manufacturers are actively addressing this issue, and specific new packaging materials tailored for RF processing are being developed.

While RF heating has a promising future in the food industry, more research is required to fully understand its complex heating mechanism and to make it applicable for food safety applications.

Overall, RF processing technology has the potential to revolutionize the food industry, offering numerous benefits over conventional heating methods, but continued research and development are necessary to address existing challenges and optimize its application.

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