Dielectric Heating: A Review of Liquid Foods Processing Applications

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Short title

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Dielectric heating is one of the most promising alternatives to conventional thermal treatment of fluid foods. The higher thermal efficiency and better heating uniformity of radio frequency and microwave processes have been proven successful in providing a similar or better bacterial and enzymatic inactivation in liquid and semi-solid foods while improving the sensory and nutritional quality of the fresh product when compared to conventional pasteurization. However, further investigations are necessary to advance scaling up of applications at different frequencies and to better understand heat distribution and energy consumption of industrial dielectric heating operations.

Keywords: dielectric heating, dielectric properties, liquid foods, microwave, radio frequency

Introduction

Thermal pasteurization and sterilization are fundamental operations in the processing of fluid foodstuffs. They are widely used to destroy pathogenic and spoilage microorganisms, as well as to inactivate enzymes responsible for quality deterioration during storage.[1]

Conventional thermal processing (CP) of liquid and semi-solid foods is done by heat exchangers, where the product flows while in indirect contact with a heating medium, usually hot water, or steam. This operation has the disadvantage of causing over-heating near the tube surfaces and requiring long heating times, which often compromises flavor, texture, and color of the final product and causes loss of nutritional components.[2]

In recent years, there is a growing consumer demand for sustainable, healthy, and high quality products which should be shelf-stable but also possess the sensory and nutritional qualities of the fresh product.[1] Therefore, the development of less aggressive alternatives to conventional thermal treatment is of great interest.[3]

Dielectric heating has the potential to provide faster and more uniform heating rates, while requiring less floor space and water input.[4] In this technology, heat is created within the material without the need for a temperature differential. This volumetric heating effect is not possible with any other conventional mean and it reduces or eliminates the temperature differences between external and internal layers, typical of conventional conduction mechanisms. [5] Dielectric heating has been reported to possess higher efficiency in the electric consumption and transformation into thermal energy when compared to convective heating.[6]

Two different regions of the electromagnetic spectra are used in dielectric heating: Radio frequency (RF) over a frequency range from 10 kHz to 300 MHz, and microwave (MW) over a frequency range from 300 MHz to 300 GHz. Five frequencies have been allocated for industrial, scientific and medical applications: 13.56, 27.12, and 40.68 MHz in the RF region and 915 and 2450 MHz in the MW region.[7]

RF heating was first used in 1895 and it has a wide range of applications in the wood, textile, paper, and cardboard industries. However, lack of research funding, lack of knowledge among the equipment manufacturers and lack of general awareness of its potential advantages have made their applications in the food industry not as prevalent as expected. Throughout the years, its major uses in the food industry have been in defrosting and post-bake drying processes.[8, 9]

MW heating of food exists since 1949, and in recent decades it has become the norm in domestic applications, changing food preferences and preparation methods. [10] However, further understanding and optimization of the temperature distribution within the product is required for industrial applications.[11]

This review aims to address a revision about the advances of dielectric heating, with a focus on its application on the thermal treatment of liquid foods and beverages. This paper is divided in eight sections: Scientific principle, dielectric properties, applications, microbiological considerations, nutritional aspects, sensory aspects, computational simulation and finally combination of dielectric heating with other novel technologies.

Scientific Principle

Foods are usually materials with high content of water and other polar compounds. When subjected to an external electric field, polar molecules in food behave like a dielectric in a capacitor, orientating towards the direction of the applied field. This behavior is described by the dielectric permittivity (ε) of the material. The intensity of the electric field is then reduced relative to what it would be in free space by a factor of ε_r, which is the value of permittivity of a given material divided by that of vacuum (ε_0):

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \qquad (1)$$

For air, relative permittivity is very close to 1. For foods, dielectric permittivity is the main parameter that defines the electromagnetic energy absorption, reflection, transmission and dissipation.[12] In general terms, the dielectric activity of liquid foods is determined less by physical structure like in solid matrices and more by the dielectric behavior of water molecules and the mobility of solutes.[13]

The response of materials to alternating electric fields such as those of electromagnetic radiation is characterized by their complex permittivity:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \qquad (2)$$

Where the real component ε' is often referred to as dielectric constant and is related to energy storage, while the imaginary component ε'' is called the dielectric loss factor, which is related to the thermal conversion.[8] The values of dielectric constant and loss factor are collectively referred to as the dielectric properties of the material.

In general terms, high moisture foods present a dielectric constant which decreases with frequency, this is caused by a faster alternation of the electromagnetic field which makes it more difficult for water molecules and clusters to orientate and polarize. Increasing temperature increases the Brownian motion of the water molecules which reduces the energy storage.[14] Replacing water for less polarizable substances e.g. oil will also result in a reduced values of ε'.[15] In solid foods, adding salt can cause binding of water molecules reducing their polarization, but this effect is often negligible in liquid foods.[16]

Thermal conversion occurs by two main mechanisms: dipole relaxation and ionic conduction. Therefore, the loss factor can be divided into its two main components as follows:

$$\varepsilon'' = \varepsilon_{\sigma}'' + \varepsilon_{d}'' \quad (3)$$

Where ε_{σ}'' is the relative ionic loss and ε_{d}'' is the relative dipole loss.[8]

Ionic loss occurs as a result of a net movement of dissolved ions in the direction of the electric field, resulting in a higher macroscopic energy of movement and a subsequent rise in temperature.[17] Ionic conduction is the dominant dissipation mechanism at low frequencies, decreasing linearly in a log-log plot against frequency. Ionic loss is directly proportional to ionic conductivity, therefore, the loss factor increases with increasing temperature or salt concentration.[7, 16]

Dipole loss is caused by individual molecules of water and clusters of molecules aligning themselves in the direction of the electric field. Clusters realign themselves with some delay, not all energy is recovered and part of it is absorbed because of a net increase in molecular movement. At high frequencies, dipole relaxation becomes the main loss mechanism, and it increases at lower temperatures due to the relaxation times of water molecules approaching the frequency of the applied electromagnetic field. If the frequency is too high, however, clusters will not have enough time to rotate. The frequency at which the energy absorption capability by the relaxation effect reaches a maximum, is called relaxation frequency.[17]

Heating liquid foods causes a much higher increase in their loss factor compared to solid matrices, since there is more ion mobility and viscosity effects.[18] Figure 1 shows the contribution of both loss mechanism at different frequencies and the effect of changes in temperature.

Predictive models of heating rates and temperature distribution require knowledge of the dielectric properties of the product. The amount of heat (provided to a material from electromagnetic energy can be calculated from the value of loss factor as follows:

$$P = 2\pi f \varepsilon_0 \varepsilon'' \left|\vec{E}\right|^2 \quad (4)$$

Where P is the power by volume unit, f is the frequency and E the local intensity of the electric field, which is also dependent on the dielectric properties.[19]

Power penetration depth of microwaves can be obtained from the dielectric properties of a material and is applied in determining the dimensions of the food materials being processed.[20]

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)}} \quad (5)$$

Where d_p is penetration deep, and c is the speed of light in vacuum. Penetration depth can be described as the depth from the surface of the product at which the power density has decreased 37 %,[21] or the microwave field has reduced to $1/e$.[22] The thickness of a liquid being heated using dielectric heating should not exceed 2 or 3 times the penetration depth.[23] Since penetration depth is inversely proportional to frequency, RF heating has the potential for better heating uniformity than MW processes.[24]

Measurement of the Dielectric Properties

Accurate measurement of dielectric properties is of great importance in industrial applications, it is essential in designing heating applicators, selecting optimal frequency ranges, formulating new products and selecting package sizes and materials.[25] Not surprisingly, dielectric properties have been extensively studied in fluid foodstuff such as fruit juices, sauces, purees, wine, honey, and milk.

The most common method for the measurement of dielectric properties of liquid and semi-liquids foods is the open-ended coaxial probe method. This method is based on the fact that the phase and amplitude of the reflected signal on an open-ended coaxial line attached to a material is dependent on its dielectric properties. The coaxial cable is connected to a network analyzer which interprets the complex reflection coefficient of the sample to obtain the dielectric properties in a determined frequency sweep. It is a non-invasive non-destructive method suitable for a wide range of temperatures, however it is not suitable for small samples or materials of very high permittivity.[26]

Table 1 shows studies on the dielectric properties of liquid foods using the coaxial probe method. It can be seen than most studies deal with temperatures below 100 ºC, beyond this point boiling of the sample can result in the formation of bubbles on the probe's surface, affecting the measurement. However, during industrial heating processes, it is common to deal with temperatures beyond the boiling point under pressurized conditions. Muñoz et al.[27] dealt with this limitation by using a pressurized vessel equipped with a heating jacket, managing to measure the dielectric properties of milk at temperatures up to 150 ºC.

Dielectric properties can be correlated with different parameters for use in quality control of liquid foods. Zhu et al.[28] developed models to relate the dielectric properties of raw milk with the protein content, making it possible to develop a real-time, in-situ method for quality control in the milk industry. Inokuchi et al.[29] measured the dielectric properties of yogurt homogenized with an air pump to obtain a method to analyze the content of air bubbles in yogurt. Guo et al.[30] measured the dielectric constant and loss factor of several honey-sucrose syrup mixtures to evaluate its potential as a tool for detecting adulteration in honey. Guo et al.[31] measured the dielectric properties of cow's milk adulterated with water to obtain a frequency suitable to detect adulteration. They also found a correlation between pH and loss factor, making it possible to correlate it to the product's freshness. García et al.[32] made daily measurements of the dielectric properties of grape juice from 200 to 3000 MHz at 20 ºC during its fermentation in the production of red wine. They found that the adherence of CO_2 bubbles to the probe gave unreliable measurements but that it could be useful to determine the extent of fermentation.

Applications

Dielectric heating technology has been successfully applied in several food products for operations such as blanching, thawing, disinfesting, drying, baking, and cooking. Even with the current limitations, some of these applications have found their way in the industry and are currently applied in large-scale processes.[24, 33]

Regarding liquid and semi-solid foods, recent research has focused on pasteurization and sterilization, with fewer studies exploring the applicability in operations such as evaporation and leaching. A number of successful MW technology applications can be found in literature for liquid foods such as fruit juices,[34–36] milk,[37, 38] purees,[39, 40] smoothies,[3] sauces,[41] sugarcane juice,[42] massecuite,[43] creams,[44] and peanut beverages.[5] RF heating has been applied to liquid foods to a much lesser extent, but its use has also been reported in milk,[45] kiwi puree,[46] yogurt,[47] fish soup,[48] and liquid egg.[49] For both technologies, the sensory and nutritional quality, as well as the heating rates and associated inactivation kinetics have been investigated, with emphasis on the comparison with CP treatments.

Microbial Inactivation using Dielectric Heating

Despite posing several advantages compared to CP of liquids and semi-solids, the industrial use of dielectric heating for microbial inactivation is not as widespread as for other operations such as dehydration, baking or thawing. One of the reasons is that there is still some lack of knowledge about the kinetics of pathogen inactivation in foods during RF and MW exposure.[39] Table 2 shows recent research aimed at better understanding this process.

Across the available literature, it is widely reported that dielectric heating technology allows for higher inactivation efficiencies of pathogenic bacteria than CP. Qualitative tools to predict inactivation levels during dielectric heating treatments have been developed for a number of liquid foods and these models can even be associated to the dielectric properties of the raw material. Kim et al.[41] subjected samples of chili sauce with different sugar contents to heating at 1.5 and 3 kW in a 915 MHz microwave cavity applicator to evaluate the inactivation efficiency on *E. coli* O157H7, *S.* typhimurium and *L. monocytogenes*. They found higher loss factor in samples with less sugar content, which resulted in shorter times to reach the target temperature. Authors also report that MW technology required a shorter time to achieve pathogen inactivation than CP using a water bath.

The higher thermal efficiency observed in dielectric heating has resulted in claims of non-thermal effects associated to this technology. The most predominant theories to explain this phenomena were selective heating of microorganisms, electroporation, cell membrane rupture and magnetic field coupling.[50] Over the years, and with the development of more accurate methods to record time-temperature history, non-thermal effects became harder to distinguish. There is still controversial discussion taking place but currently, thermal effects are generally considered the only cause of microorganism inactivation at industrial RF and MW frequencies.[51]

Kou et al.[51] suggest that claimed non-thermal effects were due to non-uniform experimental temperature distributions with unprecise real-time temperature control. They designed a *thermal death time* heating block to simulate the temperature-time curve obtained with RF heating and compared the reduction of *E. coli* and *S. aureus* counts on apple juice and potato puree with RF heating at 27.12 MHz, evaluating temperature uniformity and surface temperature. After reaching same heating conditions, they found similar surviving patterns for both methods and no statistical difference in bacterial inactivation.

Thermal treatments also have an important role as a mean of reducing the population of spoilage microorganisms, allowing for an extended shelf life and an improvement of the sensory properties of the product. Siefarth et al.[47] applied a water bath RF heating system to reduce the population of lactic acid bacteria and molds/yeasts in yoghurt to avoid post-acidification. They evaluated three temperatures (58 °C, 65 °C and 72 °C) and applied CP using a convection oven for comparison. They found microbial reductions for both treatments, showing a potential increase in shelf-life. Furthermore, higher heating rates were obtained when using RF technology.

To evaluate the efficacy of a pasteurization process using a continuous-flow MW heating system, Math et al.[52] inoculated several blends of fruits and vegetables and evaluated the reductions in yeasts/molds count, total aerobic count and *Enterobacteriaceae* after treatment and during storage. Authors report total reduction of *Enterobacteriaceae* and yeasts/molds after treatment, as well as satisfactory counts during storage. Cheng et al.[53] determined the reduction in total aerobic count of mandarin juice treated with MW at 90 °C for 70 s. They found > 2 log reductions after processing. Lyu et al.[46] compared the reduction in yeasts/molds and total aerobic count of kiwi puree after non-continuous CP and RF treatments with the unpasteurized product. They found no differences between treatments regarding yeasts/molds reduction.

Authors also report a retarded growth of total aerobic bacteria in RF samples during storage but within acceptable limits.

Even if the presence of non-thermal effects has failed to be successfully proven in RF and MW technology, the higher thermal efficiency and better temperature distribution in dielectric heating operations have proven to allow for microbial reductions similar or higher than those of CP processes.

Nutritional Aspects

High temperature processing can lead to degradation of thermolabile nutrients and volatile compounds. The greater thermal efficiency of dielectric heating results in higher preservation of thermosensitive compounds such as vitamin C, flavonoids, and anthocyanins.[54] MW heating has shown capacity to better retain bioactive compounds, often resulting in higher antioxidant activity than the same product obtained by CP processes. In continuous-flow dielectric heating, this effect is enhanced by lower tube surface temperatures and less overheating.[1] Table 3 summarizes the related research in recent years.

Beneficial nutritional changes produced as a consequence of thermal treatments have also been investigated for dielectric heating processes, Yu et al.[55] found that during microwave heating of tomato puree mixed with onion and olive oil, combinations of high power and short heating time resulted in an increased lycopene isomerization and transfer into oil. Authors also report that their recent data indicates higher proportion of Z-lycopene after microwave heating in comparison with CP. Arjmandi et al.[56] reported higher lycopene content increase in tomato, carrot, pumpkin, and lemon smoothies after using continuous-flow MW treatment in comparison with CP process, attributed to a higher cell-wall disruption. They also reported higher total antioxidant capacity, total carotenoids content, total phenolics, total antioxidant capacity and vitamin C.

Stratakos et al.[57] were the firsts to compare MW and CP products by simulating digestion with a model of epithelial tissue absorption combined with an in-vitro model. They found a significantly higher cytoprotective effect of continuous-flow MW treated tomato juice against H_2O_2 induced oxidation in human intestine cells, suggesting higher antioxidants content in bioaccesible fractions.

In milk, microwave treatment has been reported to provide partial hydrolysis of proteins into peptides with antihypertensive activity. Martins et al.[54] analysed the antihypertensive activity of microwave-treated orange juice milk beverages by measuring the angiotensin I-converting enzyme inactivation, they found higher enzyme inhibition by treating with a lab-scale MW digester in comparison with CP process using a heating mantle.

Current literature suggests that it is possible to enhance the nutritional properties of thermally processed foods by making use of the higher thermal efficiency and better nutrient extraction of dielectric heating technology. Food products of high nutritional value are, more than ever, increasingly demanded by consumers. It is important to note that the nutritional value is directly related to other quality parameters such as color, flavor, and stability during storage.

Sensory Aspects

Color

According to Cheng et al.[53] color is the main index for consumer's quality evaluation of fruit and vegetable juices. Dielectric heating technology has been extensively reported to allow for higher color retention after processing when compared to CP. This has been observed in products such as kiwi puree,[39] [46] strawberry puree,[1] tomato puree,[56] faba bean pesto sauce,[58] and mandarin juice.[53] This phenomenon is generally attributed to a higher retention of pigments such as anthocyanins, lycopene, carotenoids.

González-Monroy et al.[59] compared the color of MW pasteurized tamarind beverages with untreated samples, they found no statistical difference in any of the colorimetric coordinates. These results are similar to those reported by Garnacho et al.[60] on MW treated orange juice and suggest a good color retention during the process. As stated before, faster heating rates and better temperature uniformities translate to lower thermal degradation of pigments which in turn makes it possible to better preserve the color of the fresh product.

Stratakos et al.[57] found no difference in the color parameters of tomato juice treated with continuous-flow MW and CP, possibly related to the fluctuations of the antioxidant capacity of the samples during storage.

Surface overheating during continuous-flow heating of dairy products can cause Maillard reactions which lead up to product browning and off-flavors. Reduced color changes after MW treatment of dairy products has been observed in products such as milk[61] and orange juice milk beverages.[54]

Flavor

Heat treatments can lead to degradation or formation of components responsible for characteristic flavors in fresh juices and purees, resulting in desirable or undesirable deviations from the fresh product. [54] In this regard, profiling the volatile compounds and organic acids of different liquid foods before and after dielectric heating processes has been subject of study in recent years.

Igual et al.[62] compared the stability during 2 months of refrigerated storage of MW and CP treated grapefruit juice. They found higher retention of citric acid after MW processing, and no differences in malic acid or tartaric acid between treatments. Siguemoto et al.[36] compared the organic acid and volatile compound profile of continuous-flow MW and CP treatment of apple juice with fresh juice. They found that the volatile profile of MW juice was closer to that of untreated juice, they also found 1-heptanol exclusively in MW juice, which is associated with leafy green and fresh notes. When comparing MW treated mandarin juice with CP and fresh juice, Cheng et al.[53] found a greater number of different aroma components and intermediate concentrations in MW treated juice. Martins et al.[54] found that orange juice milk beverages treated with CP, had a higher number of volatile organic compounds than the fresh product, both desirable and undesirable. The authors recommend MW technology at low temperatures since it provided a profile of volatile organic compounds associated with a sweet and fruity aroma absent in the fresh product.

In addition to the flavor compound profiling, sensory analysis has proven to be a powerful tool to evaluate flavor changes associated to thermal treatments, helping to understand consumer expectations on emerging technologies and what information affects their decisions. [39] Better acceptability scores after a dielectric heating process compared to CP have been reported in fish soup, [48] kiwi puree, [39, 46] strawberry puree, [1] apple puree, [46] and faba bean pesto sauce. [58]

Clare et al.[61] compared milk treated by an indirect steam injection system with milk treated with a continuous-flow MW heating unit over 12 months of storage using a descriptive sensory analysis. They found that at all time points, MW milks had less brownish hues, less fatty flavors, less astringency, and lower caramelized flavor.

Enzymatic inactivation

Enzymatic inactivation is vital to ensure quality stability of fruit juices after a thermal treatment and during storage. Polyphenol oxidase (PPO) and peroxidase (POD) are responsible for discoloration and the development of off-flavors, pectin methyl esterase (PME) and polygalacturonase (PG) destabilize the colloidal suspension of juices causing turbidity losses, clarification and changes in the characteristic mouth feel. Table 4 shows recent research on enzyme inactivation using dielectric heating technology.

Viscosity of semi-solid foods is associated to PME and PG inactivation since these enzymes are responsible for pectin hydrolysis and changes in soluble pectin content. When compared to CP treatment, Arjmandi et al.[3] found higher viscosity in continuous-flow MW treated vegetable smoothies, which also had the lowest residual activity of PME, PG and POD. Zhou et al.[63] found higher viscosity in defatted avocado puree after MW treatment. According to the authors, this change provides a better mouthfeel in the product and is caused by an increase in the soluble pectin content.

Enzyme inactivation can be used as a lethality reference for pasteurization treatments due to their higher thermal resistance than most microorganisms. Lin et al.[64] compared the alkaline phosphatase activity in milk after continuous-flow MW heating and CP using a water bath. They found faster inactivation using MW technology suggesting adequate pasteurization with a reduced severity.

Some authors have suggested that microwaves might affect the non-covalent bonds of polar or charged fractions of enzymes affecting their functionality in a different manner that thermal treatments.[65] However, this is not in accordance with some of the findings shown in table 3. When performing comparison studies between CP and dielectric heating or other novel technologies, it is important to maintain a strict control of the time-temperatures histories of the samples, as well as the source of the enzymes. Regardless of this, the lower accumulated lethality possible with RF and MW processes may facilitate the production of liquid and semi-solid foods of enhanced overall quality.

Computational Simulation of Continuous-flow Dielectric Heating Processes

In the dielectric heating of liquids, convective heat transfer plays a major role in temperature distribution. This makes possible to obtain a higher heating uniformity during continuous-flow applications by adjusting pipe diameters, flow rates and system geometry.[66] This convection phenomenon, however, makes the predictive modeling of temperature profiles considerably more challenging than in solid matrices, which is still one of the major limiting factors to the popularization of this technology. Uneven temperature distributions can have a detrimental effect on the quality of the product and compromise microbial safety.[11]

With the growing calculation capacity of modern-day computers, more detailed predictive-modelling of the distribution of electromagnetic energy during continuous-flow RF and MW heating is becoming more accessible. The usual approach requires the simultaneous solution of Maxwell's equation for electromagnetic field distribution, Navier-Stokes' equation for conservation of momentum and Fourier's energy equation for electromagnetic power absorbance and dispersion into heat. Knowledge of the temperature dependence of the dielectric and thermal properties of the materials is therefore essential for accurate calculations.

Ratanadecho et al.[67] were the first to investigate heating resulting from MW power absorption on a liquid layer in a rectangular waveguide comparing it with experimental data. They used finite difference time domain to develop a model including the electromagnetic, hydrodynamic, and heat fields in two dimensions. They performed it on water and on a NaCl solution, demonstrating the effect of dielectric properties on the heat distribution of liquids during dielectric heating.

Zhu et al.[68] used a similar approach to analyze forced convection in a liquid flowing through a rectangular duct during MW heating of apple sauce, skim milk and tomato sauce. They also analyzed the effect of applicator size and position within the MW cavity. Later, the same authors would do a similar study in a circular pipe with a geometry that better resembled industrial applications. They found that increasing pipe diameter increased power absorption up to a critical diameter.[69]

Cha-um et al.[70] studied the dependence of temperature profile on MW power, waveguide position, size and thickness of water and oil samples. Obtained results showed a good fit of the model when compared to experimental data.

To make these calculations in a less computationally extensive way and obtain better result visualization, Salvi et al.[71] used COMSOL Multiphysics to obtain the temperature distribution in water and in a carboxymethylcellulose solution during continuous MW heating accounting for temperature dependent properties and phase change.

More recently, Tuta and Palazoğlu[19] used a similar model with COMSOL Multiphysics using water and carboxymethylcellulose but evaluating the effect of helical tubes to obtain secondary flow and better temperature uniformity. From the Dean and Reynolds numbers, they only found secondary flow in water but better temperature uniformity in both liquids due to the microwaves entering from different surfaces in the coil. Zhang et al.[72] expanded on this, analyzing the effect of different structural parameters of helicoidal tubes on the heating efficiency of the MW treatment. They conclude that parameters such as tube and pitch circle diameters influence the extent of secondary flow and power distribution.

Kubo et al.[11] prepared a model fruit juice using sucrose, citric acid, horseradish POD and distilled water. They coupled enzyme inactivation kinetics with the electromagnetism, heat transfer and fluid flow equations to investigate the validity of modelling lethality at each point of the sample's volume and each instant of time. Authors conclude that other inactivation models can be implemented with this approach, making it possible to correlate holding times and incident energy to specific process targets.

Literature shows that temperature distribution during dielectric heating of fluid and semi-solid foods can be predicted accurately if there is detailed knowledge of dielectric properties and equipment dimensions. This information is critical to evaluate if sufficient heating rates can be obtained for different products and different process parameters, allowing for a better process control overall.

RF technology has the potential to provide even better temperature uniformity due to much longer penetration depths; however, most of the available literature regarding predictive modeling of RF processes deals with solid food matrices. Future years will probably see a growing interest in computational modeling of dielectric heating operations to enhance uniformity and to obtain spatial distributions for inactivation of enzymes and pathogenic microorganisms.

Combination of Dielectric Heating and other Technologies

In recent years, there has been a growing interest in looking for possible synergistic effects between dielectric heating and other new technologies. This line of research could lead to overcoming the drawbacks of each individual process and achieve higher quality preservation after treatment and during storage with less heat input.

Rayman and Baysal[73] used electroplasmolysis as a pre-treatment for MW and CP processing of carrot juice pasteurization evaluating quality parameters after treatment and during storage. They found higher phenolics content, carotenoids, PME inactivation and antioxidant activity when combining electroplasmolysis and MW compared to the control samples.

Zhang et al.[74] processed kiwi fruit using RF technology combined with the addition of nisin, a bacteriocin obtained from *Lactococcus lactis* subsp. Lactis. to reduce spores of different strains of *Alicyclobacillus acidoterrestris* and *Alicyclobacillus contaminans*. They reported a positive effect of RF treatment time, temperature, and nisin concentration on spore reduction.

Alvi et al.[42] measured the antioxidant activity, evaporation rate, color, energy consumption and solubility index of MW-assisted evaporated sugarcane juice at different power levels. They found that evaporation rate increased, and antioxidant activity decreased for increasing power levels. They also found a higher solubility index when compared to the juice evaporated using the conventional process, which indicates a good reconstitution quality.

Das et al.[75] used response surface methodology to optimize the treatment of bottle gourd juice using MW and ultrasound technology. Response variables were *L. monocytogenes* cell viability, and content of total phenolics, terpenoids and ascorbic acid. They found superior juice quality parameters and higher bacterial inactivation when combining both technologies. When compared to CP, they found higher antioxidant activity, vitamin content, higher protein content and less color change.

To produce a shelf-stable milk with improved nutritional and sensory qualities, Graf et al.[76] developed a process to separate skim milk into two fractions using microfiltration, and subsequently treat each of them using CP or MW heating according to their constituents.

Finally, there is recent literature focused on the use of dielectric technology to assist operations not related to pasteurization. Chua and Leong[77] studied the effect of sample size and evaporation rate on the quality parameters of concentrated pineapple juice obtained by MW assisted evaporation. They found low activity of proteolytic enzymes and low browning at high mass evaporation rates, associated with longer MW heating times.

Yu et al.[78] used MW technology and ultrasound in the leaching of jujube juice and compared it with conventional leaching. They found higher total soluble solids, higher soluble pectin, less protopectin, higher galacturonic acid and less pectinase activities applying ultrasound before MW.

When comparing rotary evaporation of orange juice with MW vacuum evaporation at different pressures, Bozkir[79] found higher evaporation rates in the latter, accompanied by smaller color changes and lower degradation rates of vitamin C, total phenolics and total carotenoids.

Future Trends and Prospective

Over the past 10 years, the effect of dielectric heating on microbial reduction, enzyme inactivation and preservation of nutritional and sensory quality of liquid and semi-solid foods has been extensively investigated. Comparison with conventional thermal treatments have shown that it is possible to obtain a shelf-stable, high-quality product in compliance with food safety regulations. To widen the field of applications of dielectric heating technology in liquid foods, there is scope for improvement in the following areas:

- Increasing the available data on the dielectric properties of different liquid foods, with special emphasis on temperatures above the boiling point under pressurized conditions.
- Further advancing temperature profile mathematical modelling, specially of RF heating applications since it is currently limited to solid foodstuffs.

- Expanding the current research to 13.56, 40.68, and 915 MHz, frequencies which have been investigated to a lesser extent and could offer advantages in diverse applications.
- Advancing the scaling-up of dielectric heating applicators of novel geometric design, accompanied by an evaluation of resource use and environmental impact.
- Further investigations about the possible synergistic effects of MW and RF heating with other technologies to overcome the current limitations.
- Correlate heat generation in fluid products with energy consumption in order to optimize heating process.
- Develop simple life cycle assessment decision support tools to conduct dielectric heating process

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Declaration of Interests Statement

The authors report there are no competing interests to declare.

References

[1] Marszałek, K.; Mitek, M.; Skąpska, S. Effect of Continuous Flow Microwave and Conventional Heating on the Bioactive Compounds, Colour, Enzymes Activity, Microbial and Sensory Quality of Strawberry Purée. *Food Bioprocess Technol.*, **2015**, *8* (9), 1864–1876. https://doi.org/10.1007/s11947-015-1543-7.

[2] Siguemoto, É. S.; Pereira, L. J.; Gut, J. A. W. Inactivation Kinetics of Pectin Methylesterase, Polyphenol Oxidase, and Peroxidase in Cloudy Apple Juice under Microwave and Conventional Heating to Evaluate Non-Thermal Microwave Effects. *Food Bioprocess Technol.*, **2018**, *11* (7), 1359–1369. https://doi.org/10.1007/s11947-018-2109-2.

[3] Arjmandi, M.; Otón, M.; Artés, F.; Artés-Hernández, F.; Gómez, P. A.; Aguayo, E. Continuous Microwave Pasteurization of a Vegetable Smoothie Improves Its Physical

Quality and Hinders Detrimental Enzyme Activity. *Food Sci. Technol. Int.*, **2017**, *23* (1), 36–45. https://doi.org/10.1177/1082013216654414.
[4] Salvi, D.; Ortego, J.; Arauz, C.; Sabliov, C. M.; Boldor, D. Experimental Study of the Effect of Dielectric and Physical Properties on Temperature Distribution in Fluids during Continuous Flow Microwave Heating. *J. Food Eng.*, **2009**, *93* (2), 149–157. https://doi.org/10.1016/j.jfoodeng.2009.01.009.
[5] Sabliov, C. M.; Boldor, D.; Coronel, P.; Sanders, T. H. Continuous Microwave Processing of Peanut Beverages. *J. Food Process. Preserv.*, **2008**, *32* (6), 935–945.
[6] Cherbański, R. Calculation of Critical Efficiency Factors of Microwave Energy Conversion into Heat. *Chem. Eng. Technol.*, **2011**, *34* (12), 2083–2090. https://doi.org/10.1002/ceat.201100405.
[7] Liu, Y.; Tang, J.; Mao, Z. Analysis of Bread Loss Factor Using Modified Debye Equations. *J. Food Eng.*, **2009**, *93* (4), 453–459. https://doi.org/10.1016/j.jfoodeng.2009.02.012.
[8] Jiao, Y.; Tang, J.; Wang, Y.; Koral, T. L. Radio-Frequency Applications for Food Processing and Safety. *Annu. Rev. Food Sci. Technol.*, **2018**, *9* (1), 105–127. https://doi.org/10.1146/annurev-food-041715-033038.
[9] Marra, F.; Zhang, L.; Lyng, J. G. Radio Frequency Treatment of Foods: Review of Recent Advances. *J. Food Eng.*, **2009**, *91* (4), 497–508. https://doi.org/10.1016/j.jfoodeng.2008.10.015.
[10] Smith, J. S.; Hui, Y. H. *Food Processing: Principles and Applications*; John Wiley & Sons: Hoboken, NJ, **2008**.
[11] Kubo, M. T. K.; Curet, S.; Augusto, P. E. D.; Boillereaux, L. Multiphysics Modeling of Microwave Processing for Enzyme Inactivation in Fruit Juices. *J. Food Eng.*, **2019**, *263*, 366–379. https://doi.org/10.1016/j.jfoodeng.2019.07.011.
[12] Jain, D.; Tang, J.; Pedrow, P. D.; Tang, Z.; Sablani, S.; Hong, Y.-K. Effect of Changes in Salt Content and Food Thickness on Electromagnetic Heating of Rice, Mashed Potatoes and Peas in 915 MHz Single Mode Microwave Cavity. *Food Res. Int.*, **2019**, *119*, 584–595. https://doi.org/10.1016/j.foodres.2018.10.036.
[13] Ahmed, J.; Ramaswamy, H. S.; Kasapis, S.; Boye, J. I. *Novel Food Processing: Effects on Rheological and Functional Properties*; CRC Press: Boca Raton, FL, 2016.
[14] Franco, A. P.; Yamamoto, L. Y.; Tadini, C. C.; Gut, J. A. W. Dielectric Properties of Green Coconut Water Relevant to Microwave Processing: Effect of Temperature and Field Frequency. *J. Food Eng.*, **2015**, *155*, 69–78. https://doi.org/10.1016/j.jfoodeng.2015.01.011.
[15] Sosa-Morales, M. E.; Valerio-Junco, L.; López-Malo, A.; García, H. S. Dielectric Properties of Foods: Reported Data in the 21st Century and Their Potential Applications. *LWT - Food Sci. Technol.*, **2010**, *43* (8), 1169–1179. https://doi.org/10.1016/j.lwt.2010.03.017.
[16] Peng, J.; Tang, J.; Jiao, Y.; Bohnet, S. G.; Barrett, D. M. Dielectric Properties of Tomatoes Assisting in the Development of Microwave Pasteurization and Sterilization Processes. *LWT - Food Sci. Technol.*, **2013**, *54* (2), 367–376. https://doi.org/10.1016/j.lwt.2013.07.006.
[17] Risman, P. Microwave Dielectric Properties of Foods and Some Other Substances. In *Development of Packaging and Products for Use in Microwave Ovens*; Elsevier, 2009; pp 153–175. https://doi.org/10.1533/9781845696573.1.153.
[18] Coronel, P.; Simunovic, J.; Sandeep, K. P.; Kumar, P. Dielectric Properties of Pumpable Food Materials at 915 MHz. *Int. J. Food Prop.*, **2008**, *11* (3), 508–518. https://doi.org/10.1080/10942910701472755.

[19] Tuta, S.; Palazoğlu, T. K. Finite Element Modeling of Continuous-Flow Microwave Heating of Fluid Foods and Experimental Validation. *J. Food Eng.*, **2017**, *192*, 79–92. https://doi.org/10.1016/j.jfoodeng.2016.08.003.

[20] Llave, Y.; Terada, Y.; Fukuoka, M.; Sakai, N. Dielectric Properties of Frozen Tuna and Analysis of Defrosting Using a Radio-Frequency System at Low Frequencies. *J. Food Eng.*, **2014**, *139*, 1–9. https://doi.org/10.1016/j.jfoodeng.2014.04.012.

[21] Feynman, R. P.; Leighton, R. B.; Sands, M. L. *The Feynman Lectures on Physics*, New millennium ed.; Basic Books: New York, 2011.

[22] Tanaka, F.; Morita, K.; Mallikarjunan, P.; Hung, Y.-C.; Ezeike, G. O. I. Analysis of Dielectric Properties of Soy Sauce. *J. Food Eng.*, **2005**, *71* (1), 92–97. https://doi.org/10.1016/j.jfoodeng.2004.10.023.

[23] Schiffmann, R. F. Microwave and Dielectric Drying. In *Handbook of Industrial Drying,* Mujumdar, A. S., Ed. CRC Press: Boca Raton, FL, 1995.

[24] Altemimi, A.; Aziz, S. N.; Al-HiIphy, A. R. S.; Lakhssassi, N.; Watson, D. G.; Ibrahim, S. A. Critical Review of Radio-Frequency (RF) Heating Applications in Food Processing. *Food Qual. Saf.*, **2019**, *3* (2), 81–91. https://doi.org/10.1093/fqsafe/fyz002.

[25] Zhu, X.; Guo, W.; Wu, X. Frequency- and Temperature-Dependent Dielectric Properties of Fruit Juices Associated with Pasteurization by Dielectric Heating. *J. Food Eng.*, **2012**, *109* (2), 258–266. https://doi.org/10.1016/j.jfoodeng.2011.10.005.

[26] Zadeh, M. V.; Afrooz, K.; Shamsi, M.; Rostami, M. A. Measuring the Dielectric Properties of Date Palm Fruit, Date Palm Leaflet, and Dubas Bug at Radio and Microwave Frequency Using Two-Port Coaxial Transmission/Reflection Line Technique. *Biosyst. Eng.*, **2019**, *181*, 73–85. https://doi.org/10.1016/j.biosystemseng.2019.03.003.

[27] Muñoz, I.; Gou, P.; Picouet, P. A.; Barlabé, A.; Felipe, X. Dielectric Properties of Milk during Ultra-Heat Treatment. *J. Food Eng.*, **2018**, *219*, 137–146. https://doi.org/10.1016/j.jfoodeng.2017.09.025.

[28] Zhu, X.; Guo, W.; Jia, Y.; Kang, F. Dielectric Properties of Raw Milk as Functions of Protein Content and Temperature. *Food Bioprocess Technol.*, **2015**, *8* (3), 670–680. https://doi.org/10.1007/s11947-014-1440-5.

[29] Inokuchi R.; Kawai K.; Hagura Y. Effect of Dispersion Air Bubbles in Yogurt on Dielectric Properties. *Jpn. J. Food Eng.*, **2012**, *13* (1), 13–20. https://doi.org/10.11301/jsfe.13.13.

[30] Guo, W.; Liu, Y.; Zhu, X.; Wang, S. Dielectric Properties of Honey Adulterated with Sucrose Syrup. *J. Food Eng.*, **2011**, *107* (1), 1–7. https://doi.org/10.1016/j.jfoodeng.2011.06.013.

[31] Guo, W.; Zhu, X.; Liu, H.; Yue, R.; Wang, S. Effects of Milk Concentration and Freshness on Microwave Dielectric Properties. *J. Food Eng.*, **2010**, *99* (3), 344–350. https://doi.org/10.1016/j.jfoodeng.2010.03.015.

[32] García, A.; Torres, J. L.; De Blas, M.; De Francisco, A.; Illanes, R. Dielectric Characteristics of Grape Juice and Wine. *Biosyst. Eng.*, **2004**, *88* (3), 343–349. https://doi.org/10.1016/j.biosystemseng.2004.04.008.

[33] Guo, C.; Mujumdar, A. S.; Zhang, M. New Development in Radio Frequency Heating for Fresh Food Processing: A Review. *Food Eng. Rev.*, **2019**, *11* (1), 29–43. https://doi.org/10.1007/s12393-018-9184-z.

[34] Franco, A. P.; Tadini, C. C.; Wilhelms Gut, J. A. Predicting the Dielectric Behavior of Orange and Other Citrus Fruit Juices at 915 and 2450 MHz. *Int. J. Food Prop.*, **2017**, 1–21. https://doi.org/10.1080/10942912.2017.1347674.

[35] Mendes-Oliveira, G.; Deering, A. J.; San Martin-Gonzalez, M. F.; Campanella, O. H. Microwave Pasteurization of Apple Juice: Modeling the Inactivation of Escherichia Coli O157:H7 and Salmonella Typhimurium at 80–90 °C. *Food Microbiol.*, **2020**, *87*, 103382. https://doi.org/10.1016/j.fm.2019.103382.
[36] Siguemoto, É. S.; Purgatto, E.; Hassimotto, N. M. A.; Gut, J. A. W. Comparative Evaluation of Flavour and Nutritional Quality after Conventional and Microwave-Assisted Pasteurization of Cloudy Apple Juice. *LWT*, **2019**, *111*, 853–860. https://doi.org/10.1016/j.lwt.2019.05.111.
[37] Zhu, X.; Guo, W.; Jia, Y. Temperature-Dependent Dielectric Properties of Raw Cow's and Goat's Milk from 10 to 4,500 MHz Relevant to Radio-Frequency and Microwave Pasteurization Process. *Food Bioprocess Technol.*, **2014**, *7* (6), 1830–1839. https://doi.org/10.1007/s11947-014-1255-4.
[38] Pina-Pérez, M. C.; Benlloch-Tinoco, M.; Rodrigo, D.; Martinez, A. Cronobacter Sakazakii Inactivation by Microwave Processing. *Food Bioprocess Technol.*, **2014**, *7* (3), 821–828. https://doi.org/10.1007/s11947-013-1063-2.
[39] Benlloch-Tinoco, M.; Pina-Pérez, M. C.; Martínez-Navarrete, N.; Rodrigo, D. Listeria Monocytogenes Inactivation Kinetics under Microwave and Conventional Thermal Processing in a Kiwifruit Puree. *Innov. Food Sci. Emerg. Technol.*, **2014**, *22*, 131–136. https://doi.org/10.1016/j.ifset.2014.01.005.
[40] Brinley, T. A.; Dock, C. N.; Truong, V.-D.; Coronel, P.; Kumar, P.; Simunovic, J.; Sandeep, K. P.; Cartwright, G. D.; Swartzel, K. R.; Jaykus, L.-A. Feasibility of Utilizing Bioindicators for Testing Microbial Inactivation in Sweetpotato Purees Processed with a Continuous-Flow Microwave System. *J. Food Sci.*, **2007**, *72* (5), E235–E242. https://doi.org/10.1111/j.1750-3841.2007.00371.x.
[41] Kim, W.-J.; Park, S.-H.; Kang, D.-H. Inactivation of Foodborne Pathogens Influenced by Dielectric Properties, Relevant to Sugar Contents, in Chili Sauce by 915 MHz Microwaves. *LWT*, **2018**, *96*, 111–118. https://doi.org/10.1016/j.lwt.2018.04.089.
[42] Alvi, T.; Khan, M. K. I.; Maan, A. A.; Nazir, A.; Ahmad, M. H.; Khan, M. I.; Sharif, M.; Khan, A. U.; Afzal, M. I.; Umer, M.; et al. Modelling and Kinetic Study of Novel and Sustainable Microwave-Assisted Dehydration of Sugarcane Juice. *Processes*, **2019**, *7* (10), 712. https://doi.org/10.3390/pr7100712.
[43] Bento, L.; Rein, P.; Sabliov, C.; Boldor, D.; Coronel, P. C Massecuite Re-Heating, Using Microwaves. *J. Am. Soc. Sugar Cane Technol.*, **2006**, *26*.
[44] Giuliani, R.; Bevilacqua, A.; Corbo, M. R.; Severini, C. Use of Microwave Processing to Reduce the Initial Contamination by Alicyclobacillus Acidoterrestris in a Cream of Asparagus and Effect of the Treatment on the Lipid Fraction. *Innov. Food Sci. Emerg. Technol.*, **2010**, *11* (2), 328–334. https://doi.org/10.1016/j.ifset.2009.09.003.
[45] Awuah, G. B.; Ramaswamy, H. S.; Economides, A.; Mallikarjunan, K. Inactivation of Escherichia Coli K-12 and Listeria Innocua in Milk Using Radio Frequency (RF) Heating. *Innov. Food Sci. Emerg. Technol.*, **2005**, *6* (4), 396–402. https://doi.org/10.1016/j.ifset.2005.06.002.
[46] Lyu, X.; Peng, X.; Wang, S.; Yang, B.; Wang, X.; Yang, H.; Xiao, Y.; Baloch, A. B.; Xia, X. Quality and Consumer Acceptance of Radio Frequency and Traditional Heat Pasteurised Kiwi Puree during Storage. *Int. J. Food Sci. Technol.*, **2018**, *53* (1), 209–218. https://doi.org/10.1111/ijfs.13575.

[47] Siefarth, C.; Tran, T.; Mittermaier, P.; Pfeiffer, T.; Buettner, A. Effect of Radio Frequency Heating on Yoghurt, I: Technological Applicability, Shelf-Life and Sensorial Quality. *Foods*, **2014**, *3* (2), 318–335. https://doi.org/10.3390/foods3020318.

[48] Muñoz, I.; de Sousa, D. A. B.; Guardia, M. D.; Rodriguez, C. J.; Nunes, M. L.; Oliveira, H.; Cunha, S. C.; Casal, S.; Marques, A.; Cabado, A. G. Comparison of Different Technologies (Conventional Thermal Processing, Radiofrequency Heating and High-Pressure Processing) in Combination with Thermal Solar Energy for High Quality and Sustainable Fish Soup Pasteurization. *Food Bioprocess Technol.*, **2022**. https://doi.org/10.1007/s11947-022-02782-8.

[49] Zhu, J.; Zhang, D.; Zhou, X.; Cui, Y.; Jiao, S.; Shi, X. Development of a Pasteurization Method Based on Radio Frequency Heating to Ensure Microbiological Safety of Liquid Egg. *Food Control*, **2021**, *123*, 107035. https://doi.org/10.1016/j.foodcont.2019.107035.

[50] Kozempel, M. F.; Annous, B. A.; Cook, R. D.; Scullen, O. J.; Whiting, R. C. Inactivation of Microorganisms with Microwaves at Reduced Temperatures. *J Food Prot*, **1997**, *61*, 4.

[51] Kou, X.; Li, R.; Hou, L.; Zhang, L.; Wang, S. Identifying Possible Non-Thermal Effects of Radio Frequency Energy on Inactivating Food Microorganisms. *Int. J. Food Microbiol.*, **2018**, *269*, 89–97. https://doi.org/10.1016/j.ijfoodmicro.2018.01.025.

[52] Math, R.; Nagender, A.; Sameera Nayani, A.; Satyanarayana, A. Continuous Microwave Processing and Preservation of Acidic and Non Acidic Juice Blends. *Int. J. Agric. Food Sci. Technol.*, **2014**, *5* (2), 81–90.

[53] Cheng, C.; Jia, M.; Gui, Y.; Ma, Y. Comparison of the Effects of Novel Processing Technologies and Conventional Thermal Pasteurisation on the Nutritional Quality and Aroma of Mandarin (Citrus Unshiu) Juice. *Innov. Food Sci. Emerg. Technol.*, **2020**, *64*, 102425. https://doi.org/10.1016/j.ifset.2020.102425.

[54] Martins, C. P. C.; Cavalcanti, R. N.; Cardozo, T. S. F.; Couto, S. M.; Guimarães, J. T.; Balthazar, C. F.; Rocha, R. S.; Pimentel, T. C.; Freitas, M. Q.; Raices, R. S. L.; et al. Effects of Microwave Heating on the Chemical Composition and Bioactivity of Orange Juice-Milk Beverages. *Food Chem.*, **2021**, *345*, 128746. https://doi.org/10.1016/j.foodchem.2020.128746.

[55] Yu, J.; Gleize, B.; Zhang, L.; Caris-Veyrat, C.; Renard, C. M. G. C. Microwave Heating of Tomato Puree in the Presence of Onion and EVOO: The Effect on Lycopene Isomerization and Transfer into Oil. *LWT*, **2019**, *113*, 108284. https://doi.org/10.1016/j.lwt.2019.108284.

[56] Arjmandi, M.; Otón, M.; Artés, F.; Artés-Hernández, F.; Gómez, P. A.; Aguayo, E. Semi-Industrial Microwave Treatments Positively Affect the Quality of Orange-Colored Smoothies. *J. Food Sci. Technol.*, **2016**, *53* (10), 3695–3703. https://doi.org/10.1007/s13197-016-2342-5.

[57] Stratakos, A. Ch.; Delgado-Pando, G.; Linton, M.; Patterson, M. F.; Koidis, A. Industrial Scale Microwave Processing of Tomato Juice Using a Novel Continuous Microwave System. *Food Chem.*, **2016**, *190*, 622–628. https://doi.org/10.1016/j.foodchem.2015.06.015.

[58] Klug, T. V.; Collado, E.; Martínez-Sánchez, A.; Gómez, P. A.; Aguayo, E.; Otón, M.; Artés, F.; Artés-Hernandez, F. Innovative Quality Improvement by Continuous Microwave Processing of a Faba Beans Pesto Sauce. *Food Bioprocess Technol.*, **2018**, *11* (3), 561–571. https://doi.org/10.1007/s11947-017-2024-y.

[59] González-Monroy, A. D.; Ozuna, C.; Rodríguez-Hernández, G.; Sosa-Morales, M. E. Microwave Pasteurization for Natural Tamarind Beverage. Proceedings of the CSBE/SCGAB 2017 Annual Conference, Winnipeg, MB, 6-10 August 2017; p 9.

[60] Garnacho, G.; Kaszab, T.; Horváth, M.; Géczi, G. Comparative Study of Heat-Treated Orange Juice. *JMBFS.*, **2012**, 12.
[61] Clare, D. A.; Bang, W. S.; Cartwright, G.; Drake, M. A.; Coronel, P.; Simunovic, J. Comparison of Sensory, Microbiological, and Biochemical Parameters of Microwave Versus Indirect UHT Fluid Skim Milk During Storage. *Am. Dairy Sci. Assoc.*, **2005**, *88* (12), 11.
[62] Igual, M.; García-Martínez, E.; Camacho, M. M.; Martínez-Navarrete, N. Effect of Thermal Treatment and Storage on the Stability of Organic Acids and the Functional Value of Grapefruit Juice. *Food Chem.*, **2010**, 9.
[63] Zhou, L.; Tey, C. Y.; Bingol, G.; Bi, J. Effect of Microwave Treatment on Enzyme Inactivation and Quality Change of Defatted Avocado Puree during Storage. *Innov. Food Sci. Emerg. Technol.*, **2016**, *37*, 61–67. https://doi.org/10.1016/j.ifset.2016.08.002.
[64] Lin, M.; Ramaswamy, H. S. Evaluation of Phosphatase Inactivation Kinetics in Milk Under Continuous Flow Microwave and Conventional Heating Conditions. *Int. J. Food Prop.*, **2011**, *14* (1), 110–123. https://doi.org/10.1080/10942910903147841.
[65] Kermasha, S.; Bisakowski, B.; Ramaswamy, H.; Van de Voort, F. R. Thermal and Microwave Inactivation of Soybean Lipoxygenase. *LWT - Food Sci. Technol.*, **1993**, *26* (3), 215–219. https://doi.org/10.1006/fstl.1993.1047.
[66] Chandrasekaran, S.; Ramanathan, S.; Basak, T. Microwave Food Processing—A Review. *Food Res. Int.*, **2013**, *52* (1), 243–261. https://doi.org/10.1016/j.foodres.2013.02.033.
[67] Ratanadecho, P.; Aoki, K.; Akahori, M. A Numerical and Experimental Investigation of the Modeling of Microwave Heating for Liquid Layers Using a Rectangular Wave Guide (Effects of Natural Convection and Dielectric Properties). *Appl. Math. Model.*, **2002**, *26* (3), 449–472. https://doi.org/10.1016/S0307-904X(01)00046-4.
[68] Zhu, J.; Kuznetsov, A. V.; Sandeep, K. P. Numerical Simulation of Forced Convection in a Duct Subjected to Microwave Heating. *Heat Mass Transf.*, **2006**, *43* (3), 255–264. https://doi.org/10.1007/s00231-006-0105-y.
[69] Zhu, J.; Kuznetsov, A. V.; Sandeep, K. P. Mathematical Modeling of Continuous Flow Microwave Heating of Liquids (Effects of Dielectric Properties and Design Parameters). *Int. J. Therm. Sci.*, **2007**, *46* (4), 328–341. https://doi.org/10.1016/j.ijthermalsci.2006.06.005.
[70] Cha-um, W.; Rattanadecho, P.; Pakdee, W. Experimental and Numerical Analysis of Microwave Heating of Water and Oil Using a Rectangular Wave Guide : Influence of Sample Sizes, Positions, and Microwave Power. *Food Bioprocess Technol*, **2011**, 16.
[71] Salvi, D.; Boldor, D.; Aita, G. M.; Sabliov, C. M. COMSOL Multiphysics Model for Continuous Flow Microwave Heating of Liquids. *J. Food Eng.*, **2011**, *104* (3), 422–429. https://doi.org/10.1016/j.jfoodeng.2011.01.005.
[72] Zhang, Y.; Yang, H.; Yan, B.; Zhu, H.; Gao, W.; Zhao, J.; Zhang, H.; Chen, W.; Fan, D. Continuous Flow Microwave System with Helical Tubes for Liquid Food Heating. *J. Food Eng.*, **2021**, *294*, 110409. https://doi.org/10.1016/j.jfoodeng.2020.110409.
[73] Rayman, A.; Baysal, T. Yield and Quality Effects of Electroplasmolysis and Microwave Applications on Carrot Juice Production and Storage. *J. Food Sci.*, **2011**, *76* (4), C598–C605. https://doi.org/10.1111/j.1750-3841.2011.02156.x.
[74] Zhang, J. B.; Gao, Z. P.; Liu, X. H.; Yue, T. L.; Yuan, Y. H. The Effect of RF Treatment Combined with Nisin Against Alicyclobacillus Spores in Kiwi Fruit Juice. *Food Bioprocess Technol.*, **2017**, *10* (2), 340–348. https://doi.org/10.1007/s11947-016-1822-y.

[75] Das, M. J.; Das, A. J.; Chakraborty, S.; Baishya, P.; Ramteke, A.; Deka, S. C. Effects of Microwave Combined with Ultrasound Treatment on the Pasteurization and Nutritional Properties of Bottle Gourd (*Lagenaria Siceraria*) Juice. *J. Food Process. Preserv.*, **2020**, *44* (12). https://doi.org/10.1111/jfpp.14904.
[76] Graf, B.; Kohler, E.; Rosenberger, M.; Schäfer, J.; Hinrichs, J. Shelf-Stable Milk Produced by Microfiltration and Microwave Heating: Effects of Processing and Storage. *J. Food Eng.*, **2021**, *311*, 110734. https://doi.org/10.1016/j.jfoodeng.2021.110734.
[77] Chua, L. S.; Leong, C. Y. Effects of Microwave Heating on Quality Attributes of Pineapple Juice. *J. Food Process. Preserv.*, **2020**, *44* (10). https://doi.org/10.1111/jfpp.14786.
[78] Yu, Y.; Cheng, X.; Zhang, C.; Zhang, J.; Zhang, S.; Xu, J. Ultrasonic and Microwave Treatment Improved Jujube Juice Yield. *Food Sci. Nutr.*, **2020**, *8* (8), 4196–4204. https://doi.org/10.1002/fsn3.1713.
[79] Bozkir, H.; Tekgül, Y. Production of Orange Juice Concentrate Using Conventional and Microwave Vacuum Evaporation: Thermal Degradation Kinetics of Bioactive Compounds and Color Values. *J. Food Process. Preserv.*, **2021**, *n/a* (n/a), e15902. https://doi.org/10.1111/jfpp.15902.
[80] Kumar, P.; Coronel, P.; Simunovic, J.; Sandeep, K. P. Thermophysical and Dielectric Properties of *Salsa Con Queso* and Its Vegetable Ingredients at Sterilization Temperatures. *Int. J. Food Prop.*, **2008**, *11* (1), 112–126. https://doi.org/10.1080/10942910701272312.
[81] Tanaka, F.; Uchino, T.; Hamanaka, D.; Atungulu, G. G.; Hung, Y.-C. Dielectric Properties of Mirin in the Microwave Frequency Range. *J. Food Eng.*, **2008**, *89* (4), 435–440. https://doi.org/10.1016/j.jfoodeng.2008.05.029.
[82] Bohigas, X.; Tejada, J. Dielectric Properties of Acetic Acid and Vinegar in the Microwave Frequencies Range 1–20GHz. *J. Food Eng.*, **2009**, *94* (1), 46–51. https://doi.org/10.1016/j.jfoodeng.2009.02.029.
[83] Guo, W.; Zhu, X.; Liu, Y.; Zhuang, H. Sugar and Water Contents of Honey with Dielectric Property Sensing. *J. Food Eng.*, **2010**, *97* (2), 275–281. https://doi.org/10.1016/j.jfoodeng.2009.10.024.
[84] Kubo, M. T. K.; Curet, S.; Augusto, P. E. D.; Boillereaux, L. Artificial Neural Network for Prediction of Dielectric Properties Relevant to Microwave Processing of Fruit Juice. *J. Food Process Eng.*, **2018**, *41* (6), e12815. https://doi.org/10.1111/jfpe.12815.
[85] Kataria, T. K.; Corona-Chávez, A.; Olvera-Cervantes, J. L.; Rojas-Laguna, R.; Sosa-Morales, M. E. Dielectric Characterization of Raw and Packed Soy Milks from 0.5 to 20 GHz at Temperatures from 20 to 70 ºC. *J. Food Sci. Technol.*, **2018**, *55* (8), 3119–3126. https://doi.org/10.1007/s13197-018-3238-3.
[86] Abea, A.; Gou, P.; Guardia, M. D.; Bañon, S.; Muñoz, I. Combined Effect of Temperature and Oil and Salt Contents on the Variation of Dielectric Properties of a Tomato-Based Homogenate. *Foods*, **2021**, *10* (12), 3124. https://doi.org/10.3390/foods10123124.
[87] Valderrama, Á. M. V.; Arenas, R. L. S. Utilización de microondas en el tratamiento de jugo de mango. *Rev. LASALLISTA Investig.*, **2008**, *5* (2), 13–19.
[88] Picouet, P. A.; Landl, A.; Abadias, M.; Castellari, M.; Viñas, I. Minimal Processing of a Granny Smith Apple Purée by Microwave Heating. *Innov. Food Sci. Emerg. Technol.*, **2009**, *10* (4), 545–550. https://doi.org/10.1016/j.ifset.2009.05.007.
[89] Sung, H.-J.; Kang, D.-H. Effect of a 915 MHz Microwave System on Inactivation of Escherichia Coli O157:H7, Salmonella Typhimurium, and Listeria Monocytogenes in Salsa. *LWT - Food Sci. Technol.*, **2014**, *59* (2), 754–759. https://doi.org/10.1016/j.lwt.2014.05.058.

[90] Pérez-Tejeda, G.; Vergara-Balderas, F. T.; López-Malo, A.; Rojas-Laguna, R.; Abraham-Juárez, Ma. del R.; Sosa-Morales, M. E. Pasteurization Treatments for Tomato Puree Using Conventional or Microwave Processes. *J. Microw. Power Electromagn. Energy*, **2016**, *50* (1), 35–42. https://doi.org/10.1080/08327823.2016.1157315.
[91] Siguemoto, É. S.; Gut, J. A. W.; Martinez, A.; Rodrigo, D. Inactivation Kinetics of Escherichia Coli O157:H7 and Listeria Monocytogenes in Apple Juice by Microwave and Conventional Thermal Processing. *Innov. Food Sci. Emerg. Technol.*, **2018**, *45*, 84–91. https://doi.org/10.1016/j.ifset.2017.09.021.
[92] Hashemi, S. M. B.; Gholamhosseinpour, A.; Niakousari, M. Application of Microwave and Ohmic Heating for Pasteurization of Cantaloupe Juice: Microbial Inactivation and Chemical Properties. *J. Sci. Food Agric.*, **2019**, *99* (9), 4276–4286. https://doi.org/10.1002/jsfa.9660.
[93] Arjmandi, M.; Otón, M.; Artés, F.; Artés-Hernández, F.; Gómez, P. A.; Aguayo, E. Microwave Flow and Conventional Heating Effects on the Physicochemical Properties, Bioactive Compounds and Enzymatic Activity of Tomato Puree: Microwave Flow and Conventional Heating Effects on Tomato Puree. *J. Sci. Food Agric.*, **2017**, *97* (3), 984–990. https://doi.org/10.1002/jsfa.7824.
[94] Kumar, S.; Khadka, M.; Mishra, S.; Kohli, D.; Upadhaya, S. Effects of Conventional and Microwave Heating Pasteurization on Physiochemical Properties of Pomelo (Citrus Maxima) Juice. *J. Food Process. Technol.*, **2017**, *08* (07). https://doi.org/10.4172/2157-7110.1000683.
[95] Souza Comapa, S.; Carvalho, L. M. S.; Lamarão, C. V.; Souza, F. das C. do A.; Aguiar, J. P. L.; Silva, L. S.; Mar, J. M.; Sanches, E. A.; Santos, F. F.; Araújo Bezerra, J.; et al. Microwave Processing of Camu-camu Juices: Physicochemical and Microbiological Parameters. *J. Food Process. Preserv.*, **2019**, *43* (7). https://doi.org/10.1111/jfpp.13989.
[96] Benlloch-Tinoco, M.; Igual, M.; Salvador, A.; Rodrigo, D.; Martínez-Navarrete, N. Quality and Acceptability of Microwave and Conventionally Pasteurised Kiwifruit Puree. *Food Bioprocess Technol.*, **2014**, *7* (11), 3282–3292. https://doi.org/10.1007/s11947-014-1315-9.
[97] Brugos, A. F. O. Inactivation Kinetics of Pectin Methyl Esterase in the Microwave-Assisted Pasteurization of Orange Juice. *Food Sci. Technol.*, **2018**, 7.
[98] Siguemoto, É. S.; Funcia, E. dos S.; Pires, M. N.; Gut, J. A. W. Modeling of Time-Temperature History and Enzymatic Inactivation of Cloudy Apple Juice in Continuous Flow Microwave Assisted Pasteurization. *Food Bioprod. Process.*, **2018**, *111*, 45–53. https://doi.org/10.1016/j.fbp.2018.06.004.

Tables

Table 1. Selected studies on dielectric properties of liquid and semi-solid foods.

Material	Frequencies	Temperature	References
Soy sauce	300-3000 MHz	5-70 °C	[22]
Milk, soy beverages, pudding and avocado paste	915 MHz	10-90 °C	[18]
Salsa con queso	915 MHz	20-130 °C	[80]
Mirin	300-3000 MHz	5-70 °C	[81]
Peanut beverages	915 MHz	18-90 ºC	[5]
Vinegar and acetic acid solutions of different concentration	1-20 GHz	20-22 °C	[82]
Yellow locust flower honey, jujube flower honey and rape flower honey	10-4500 MHz	25 °C	[83]
Apple, orange, pear, grape and pineapple juice	20-2400 MHz	15-95 °C	[25]
Homogenate of different tomato tissues, with different concentrations of NaCl and CaCl2	300-3000 MHz	22-120 °C	[16]
Cow and Goat milk	10-4500 MHz	25-75 °C	[37]
Green coconut water	500-3000 MHz	0-90 °C	[14]
Simulated solutions of salt and sugar from green coconut water			
Citrus fruit juices and their blends	500-3000 MHz	0-90 °C	[34]
Model juice solutions and apple, pineapple and orange juices	200-3000 MHz	20-80 °C	[84]
Raw and packed soy milk formulations	500-20000 MHz	20-70 °C	[85]
Raw milk, skimmed milk, 35 % concentrated non fat milk	10-2450 MHz	20-150 °C	[27]
Tomato, salt and olive oil homogenates	10-3000 MHz	10-100 ºC	[86]

Table 2. Selected studies on RF and MW pasteurization of liquid and semi-solid foods.

Product	System	Frequency (MHz)	Power (W)	Species	Reduction (log UFC/mL)	Processing conditions	References
Milk	Continuous-flow 50 Ω RF applicator	27.12	1200	*L. innocua* *E. coli* K-12	>4.69 >7	Residence time: 55.5 s Outlet temperature: 65 ºC	[45]
Sweet potato puree	Continuous-flow, two applicator MW system at 915 MHz	915	60000	Plastic pouches bioindicators of *B. subtilis*, *G. stearothermophilus*	>4.69 for *B. subtilis*, >4.26 for *G. stearothermophilus* at 132 ºC and 138 ºC	Residence time: 25 s Temperatures: 126 ºC 132 ºC 138 ºC	[40]
Mango juice	MW oven with refractory glass spirals for continuous-flow	2450	1500	*Aspergillus.* spp.	1	Max. temperature: 52 ºC	[87]
Apple puree	MW oven	2450	652	*E. coli* O157:H7 *L. innocua*	1.01 >2.82	Treatment time: 35s Max. temperature: 75.3 ºC	[88]

Table 2. (Continued)

Product	System	Frequency (MHz)	Power (W)	Species	Reduction (log UFC/mL)	Processing conditions	References
Asparagus cream	MW oven	2450	720, 810, 900	*A. acidoterrestris*	2 for t= 5 min at 900 W, t= 6 min at 810 W, t= 7 min at 720 W	Treatment time: 3-7 min	[44]
Kiwi puree	MW oven	2450	600, 900, 1000	*L. monocytogenes*	>5 for t>75 s at 900 W and t>82 s at 1000 W	Treatment time: 50-340 s	[39]
Reconstituted powder instant formula milk	MW oven	2450	400, 500, 600, 700, 800, 900	*Cronobacter sakazakii*	>5 for 120 min at 700, 800 and 900 W	Treatment time: 30-120 s	[38]
Salsa	WR-975 Waveguide MW system with turntable and stirrer	915	1200, 1800, 2400, 3600, 4800	*S.* Typhimurium *L. monocytogenes,* *E. coli* O157:H7	5.76-6.10 4.51-4.84 5.17-6.21	Final temperature: 90 ºC	[89]

815 Table 2. (Continued)

Product	System	Frequency (MHz)	Power (W)	Species	Reduction (log UFC/mL)	Processing conditions	References
Tomato puree	MW oven	2450	950	*E. coli* O157:H7	4.88	Treatment time: 3 min	[90]
Apple juice	Adapted MW oven	2450	400, 600, 800, 1000	*E. coli* O157:H7 *L. monocytogenes*	>5 >5 At 1000 W	Treatment time: 110 s for *E. coli* 130 s for *L. monocytogenes*	[91]
Cantaloupe juice	MW oven	2450	400, 800	*E. coli* O157:H7 *S. aureus* *S. enterica* serovar Enteritidis *S.* Typhimurium	>8 for 110 s for all microorganisms	Treatment time: Up to 110 s Inactivation started from 50 s	[92]
Apple juice	MW oven	2450	720, 600	*E. coli* O157:H7 *S.* Typhimurium	>5	Treatment time: > 20 s for 720 W > 25 s for 600 W	[35]
Liquid whole egg, liquid egg white, liquid egg yolk	Parallel electrode free running RF unit	27.12	1200	*S. enterica* serovar Enteritidis	5.62 4.36 5.31	Treatment time: 220 s 285 s 180 s At different electrode gaps	[49]

Table 3. Selected studies on nutritional properties of liquid and semi-solid foods treated with dielectric heating.

Product	Dielectric heating conditions	Conventional heating conditions	Significant findings on nutritional properties	References
Grapefruit juice	MW Oven 900 W 30 s	Water bath 80 ºC 11 s	Similar reduction of antioxidant capacity for both processes Higher ascorbic acid retention in MW process and during storage	[62]
Kiwi puree	MW oven 1000 W 340 s	Stainless steel batch retort 84 ºC 300 s	No change in total tannins after processing Higher reduction of total flavonoid and phenol content, and vitamins A, C, and E after CP process	[39]
Strawberry puree	Continuous-flow MW 2450 MHz 20000W 90 and 120 ºC for 10 s 80 and 90 ºC for 7 s	Gas-heated bath pasteurizer 90 ºC 15 min	Higher degradation of polyphenols, anthocyanins, and vitamin C in CP	[1]
Tomato puree	Continuous-flow MW 96 ºC 35 s Different combinations of power and time	Thermomix 96 ºC 35 s	No differences in total phenolics content Greater reduction in antioxidant capacity and vitamin C in CP More enhancement of lycopene extraction and higher β-carotene content after thermal treatment, especially for high power/short time MW process	[93]

Table 3. (Continued)

Product	Dielectric heating conditions	Conventional heating conditions	Significant findings on nutritional properties	References
Pomelo Juice	MW oven 90 ºC	Water bath 90 ºC 15 s	Higher reduction in ascorbic acid and total phenolics content in CP Higher reduction of tannin and naringin in MW heating	[94]
Kiwi puree	RF System, time: 210 s 10000 W, 27.12 MHz Electrode gap: 105 mm	Water bath 90 ºC 60 s	Higher antioxidant capacity and retention of phenolic compounds and ascorbic acid in RF treatment	[46]
Faba bean pesto sauce	Semi-industrial semi-continuous MW oven 2450 MHz, 11 kW 85 ºC 30 s	Table-top food processor 85 ºC 5 min	Higher carotenoid content in MW compared to CP Reduction of tannins after processing only in MW Higher phenolic content in MW compared to CP No difference in antioxidant capacity between MW and CP	[58]
Apple juice	Continuous-flow MW 6000 W, 2450 MHz 70, 80, 90 ºC	Counter-current coil heat exchangers 70, 80, 90 ºC	Increase in phenolic compounds and antioxidant capacity of both thermal treatments compared to untreated juice	[36]

Table 3. (Continued)

Product	Dielectric heating conditions	Conventional heating conditions	Significant findings on nutritional properties	References
Cantaloupe juice	MW oven 400 W, 800 W Time: 110s	Water bath 27-75 °C 30 min	Higher loss of vitamin C, but lower loss of β-carotene and phenolic compounds compared to CP	[92]
Camu-camu juice	MW oven 2450 MHz 310, 625, 940 W 15, 30, 45 s	Heating bath 85 ºC 60 s	Ascorbic acid content increased after MW and decreased after CP when compared to untreated samples	[95]
Mandarin juice	MW oven 800 W, 90 ºC Time: 70 s	Water bath 90 ºC 30 s	Less reduction of ascorbic acid, higher carotenoid content, and more retention of phenolic compounds compared to CP	[53]

Table 4. Select studies on enzyme inactivation during dielectric heating of liquid and semi-solid foods.

Product	Dielectric heating conditions	Conventional heating conditions	Significant findings on enzymatic inactivation	References
Grapefruit juice	MW Oven 900 W 30 s	Water bath 80 ºC 11 s	Higher degree of POD inactivation in CP treated grapefruit juice compared to MW. Residual PME activity after both processes but within range of acceptability.	[62]
Kiwi puree	MW oven 1000 W 340 s	Stainless steel batch retort 84 ºC 300 s	Both treatments inactivated 90 % of PPO, used as indicator. MW was more effective at inactivating PPO and PME than CP.	[96]
Strawberry puree	Continuous-flow MW 2450 MHz 20000W 90 and 120 ºC for 10 s 80 and 90 ºC for 7 s	Gas-heated bath pasteurizer 90 ºC 15 min	Higher inactivation of PPO and POD in the CP treatment. POD showed lower resistance to MW heating than PPO. Best compromise between enzyme inactivation, color, and nutrient preservation for MW treatment at 90 ºC.	[1]
Orange juice	MW synthesis reactor 2450 MHz 300 W 50-90 ºC 0-60 s	Polyethylene rectangular packages in a water bath 50-95 ºC 0-60 s	A model two-fraction PME inactivation model was obtained. Better inactivation efficiency using MW Only MW reached 90 % inactivation at 60 s.	[97]

Table 4. (Continued)

Product	Dielectric heating conditions	Conventional heating conditions	Significant findings on enzymatic inactivation	References
Apple juice	MW reactor 2450 MHz 300 W 50-90 ºC 20-270 s	Polyethylene pouches inside water bath 50-90 ºC 20-270 s	A model two-fraction PME inactivation model was obtained. No evidence of non-thermal effects was found in the inactivation kinetics of PME, POD and PPO.	[2]
Apple juice	Continuous-flow MW 70, 80, 90 ºC 0.4-0.9 L/min	Heat exchanger 70, 80, 90 ºC 0.4-0.9 L/min	Enzymatic residual activities from measured temperatures and residence times along the path were predicted. MW process was closer to the ideal instantaneous heating/cooling conditions, allowing for a more efficient enzyme inactivation.	[98]
Camu-camu juice	MW oven 2450 MHz 310, 625, 940 W 15, 30, 45 s	Heating bath 85 ºC 60 s	Only 940 W showed lower activity of POD compared to CP Only 310 W/15 s showed higher activity of PPO compared to CP	[95]

Figures

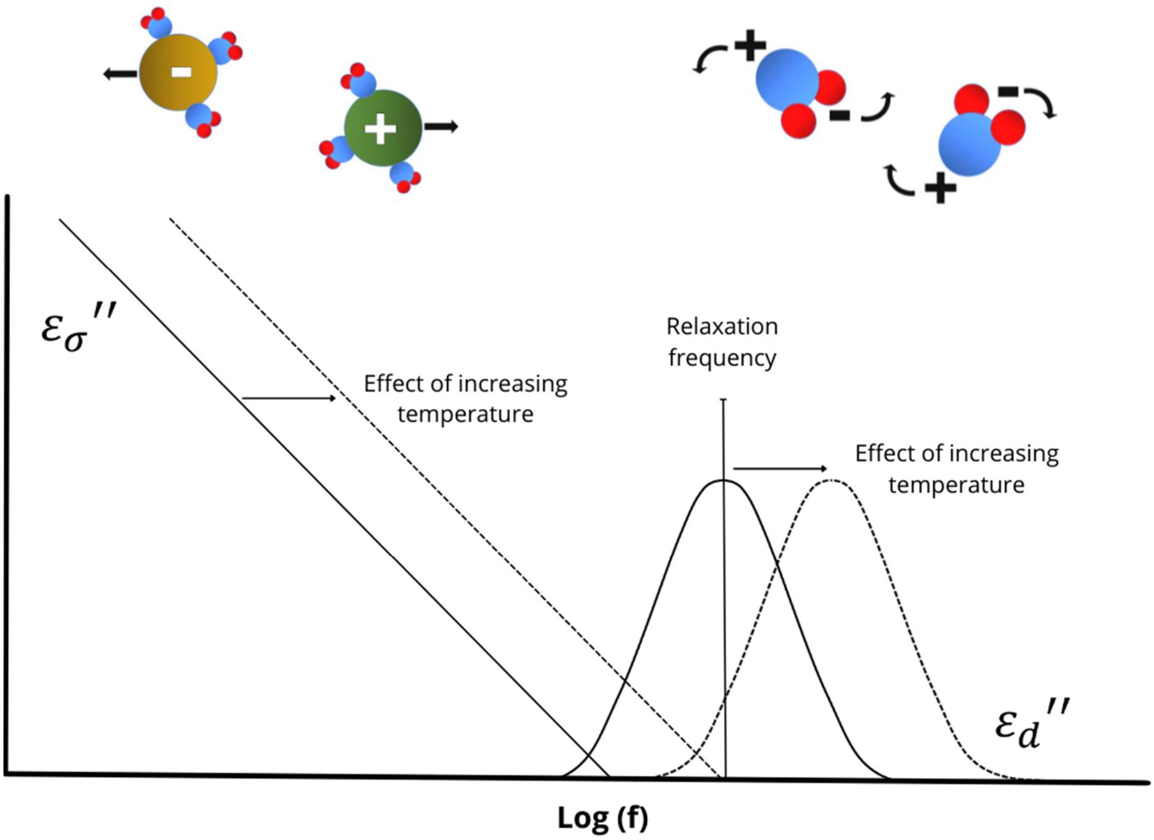
ε_σ''
Effect of increasing temperature
Relaxation frequency
Effect of increasing temperature
ε_d''
Log (f)

Figure Captions

Figure 1. Contribution of ionic conduction and dipole relaxation to the overall loss factor of materials as function of frequency.