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Effect of Dielectric Heating on the Quality and Shelf of Life of Tomato

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ABSTRACT

Tomato is a vegetable of nutritional and economic importance. It is an important part of the conventional diet and provides important vitamins for the body's development. With its short shelf life, achieving a long-term supply of tomatoes is crucial. Hence, there is a need to develop preservation technologies to improve its shelf life without significantly altering its nutritional quality. Over the years, several heating processes have been used for food preservation. These include steam and hot water heating, ohmic heating, microwave heating, and infrared processing. This study assessed the effect of radiofrequency heating on the shelf life and nutritional quality of tomatoes. The materials used were a radiofrequency signal generator (JDS6600 DDS Signal generator/counter), copper capacitance plates, plate holders, a conductivity meter (Conductometer TH27 in Siemens/m), and a few connecting wires. Fresh tomato samples were collected from farms and stored in a cool, sterile chiller during transit. Samples were chopped or shredded into a paste just before the analysis. The parallel plate capacitance method was used to determine the dielectric properties of the fruits. The dielectric properties of the fruit were measured, along with the exposure parameters, proximate analysis, and shelf life of the fruit. The work carried out shows that the frequency range to extend the shelf life of tomatoes was from 10 to 50 MHz, while the penetration depth for effective exposure at the same frequency was found to be between 0.05 m to 0.09 m. The effect of radiofrequency radiation on the proximate composition of tomatoes was found to be safe for consumption at 20 MHz with an extended shelf life of 11 days, with no significant impact on the proximate composition of the samples at the field of 55.37 – 73.43 V/m. The temperature rise for tomatoes was between 37°C to 39°C in 10 minutes.

Keywords:
Dielectric,
Radiofrequency,
Shelf-Life,
Microwave,
Pasteurization.

INTRODUCTION

Food security, as defined by the FAO, is a situation where all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences for an active and healthy life. This is crucial because it ensures a healthy and productive population that can effectively utilize resources, with all members of society contributing to development. Food security is a significant challenge in developing countries.

Fruits are the edible parts of a mature ovary of a flowering plant that can be eaten raw, while vegetables are the fleshy parts of plants that can be consumed raw, cooked, canned, or processed, providing essential nutrition to humans (Thompson *et al*., 2021). They play a critical role in achieving food security, as they provide essential dietary requirements (Charles & Arul, 2007). The vitamins, minerals, essential micronutrients, fibre, and vegetable proteins they supply are vital for balanced health and nutrition (FAO, 2015).

The seasonal nature of most fruits and their vulnerability to significant postharvest losses necessitate their preservation to ensure year-round availability and supply (Charles & Arul, 2007). Their short shelf life leads to early spoilage, limiting storage duration. Spoilage of fruits and vegetables results in severe agricultural and economic losses (Rockefeller Foundation, 2015). Therefore, developing technologies to combat fruit spoilage is essential.

Tomato (*Solanum lycopersicum*) has a high consumption rate in many developed countries and is often referred to as a luxury crop (Ajibare *et al*., 2022). Farmers are tasked with producing quantity and quality while also ensuring that fruits and vegetables stay fresh even after harvesting. It is worth noting that postharvest losses can occur at any point from harvest through collection and distribution to the final consumer. Thus, preservation is important for all stakeholders involved in the production and consumption of these vegetables and fruits.

Food irradiation is a process of preserving food in which food is exposed to appropriate doses of ionizing radiation to kill insects, moulds and other potentially harmful microbes and allergens. The radiation sources could be gamma rays, electron beams or X-rays. The radiation doses could be high, low, or medium depending on the products to be irradiated and the target organism to be eradicated. Irradiation technology has various applications including sprout inhibition in root and tubers, disinfestation in cereals and pulses, reduction or elimination of food-borne pathogens in vegetables and animal products and delayed ripening of fruits (Mshelia *et al*., 2023).

RF pasteurization has become a useful method for the preservation of fruits because fruits have high water content, leading to the polarization of water molecules when they are exposed to an external field. Energy loss processes that lead to the heating of fruits are set up, resulting in heat loss within the fruit. This process has been reported in the literature to occur without degradation of quality (Kataria *et al*., 2017). Thus, it is an innovative method of food preservation. Dielectric heating typically occurs in the absence of free carriers, nominally in non-conductive materials. This study has assessed and utilized the dielectric properties of tomatoes for pasteurization and preservation.

Dielectric Theory

The macroscopic properties of matter defining its interaction with non-ionizing electromagnetic waves are complex permittivity ε^* and complex permeability μ^* which describe the interaction of matter with electric field E and magnetic field H vectors respectively.

The dielectric properties provide in detail, how food materials interact with electromagnetic waves. Dielectric heating occurs when electromagnetic radiation stimulates the oscillation of dipoles (e.g., water molecules) in the surrounding medium. The electromagnetic energy is converted into heat. (Doshi & Keane, 2006). The propagation of MW in biological tissue is regulated by tissue composition and dielectric permittivity, source frequency and power, and antenna radiation pattern and polarization. The Debye dispersion model described in Equation (1) explains the interaction of the electric field vector with biological tissues (Pethig, 1979).

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau^2} \tag{2}$$

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1+\omega^2\tau^2} \tag{3}$$

The loss factor, ε'' is the imaginary part of the complex permittivity and it measures the rate at which electrical energy is converted to heat, ε_∞ is the high-frequency permittivity, ε_s is the static value, ω is the angular frequency and τ is the relaxation time.

In the Debye model, molecules are considered rotating spheroids with changing orientations that vary in line with an external alternating electric field. While rotating, these molecules collide with each other and the surroundings. This converts some of the rotational energy into heat. The energy absorbed by the material due to the dipole rotations and collisional relaxation leads to dielectric loss that converts the electromagnetic energy into heat which is distributed through the material through conduction and convection. The relaxation time of the molecules determines the rate of energy absorption and conversion.

The penetration depth of an electromagnetic wave is an important parameter in characterizing the temperature distribution in electromagnetic wave-heated foods and is generally used to predict the depth at which microwave energy can penetrate a material such as food. Penetration depth (D_p) is defined as the depth where the power is reduced to 1/e (e = 2.718) of the power entering the surface (Auksornsri, *et al*, 2018). Equation (4) was used to determine D_p (Ahmed *et al*., 2007):

$$D_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\sqrt{1+(\frac{\varepsilon''}{\varepsilon'})^2-1}}} \tag{4}$$

Where c is the speed of light 3×10^8ms^{-1} f is the frequency in Industries, Science and Medicine (ISM) Standard.

The relative permittivity has a greater impact on penetration depth than the loss factor (tan δ). Thus, if the loss factor is much less than 1, its influence will be minimal and (Equation. 6) can be rewritten as seen in Equation (5).

$$D_p = \frac{c}{2\pi f\sqrt{\varepsilon' tan\delta}} = \frac{4.77\times10^7}{f\sqrt{\varepsilon' tan\delta}} \tag{5}$$

MATERIALS AND METHODS

Fresh Tomato samples were collected from the farm and stored in a cool, sterile chiller during transit. The samples were shredded into a paste just before the analysis to ensure temperature homogeneity across the sample as described by Kataria *et al*., (2017). A sample cell utilizing the parallel plate capacitance technique was constructed for measuring the dielectric properties of the fruit measured using the resonance technique (See Figure 1). This utilized a conductivity meter (Conductometer TH27) and a signal generator (JDS 6600 DDS, US). The sample cell contained copper electrodes of diameter 0.6 cm. The residual capacitance of the cell and cell constant were determined from measurements on air and distilled water. The results obtained were used to correct for electrode polarization effect at low frequencies and stray capacitance at higher frequencies by determining the appropriate plate separation for measuring the dielectric properties of the tomato samples to be tested (Agba, 2017; Laogun *et al*., 1997).

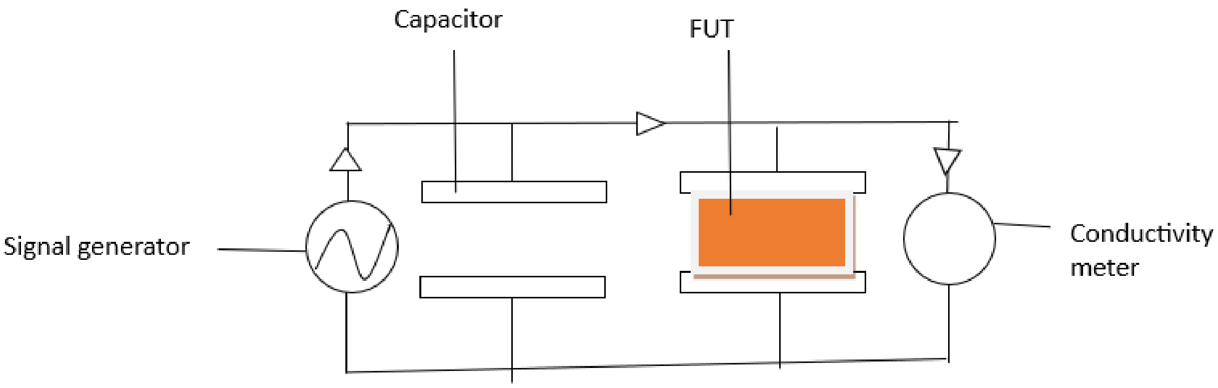

Figure 1: Circuit diagram for sample cell for dielectric measurements

To determine the dielectric properties of fruits, 20 g of paste from each sample was placed in the sample cell with the paste placed in the sample holder with 8 cm interelectrode separation. The plate had contact with the sample, and air bubbles between the plates and the material under testing were eliminated. The initial sample temperature was 25°C, and the readings were taken at the end of timed radiofrequency irradiation. Ten readings were taken after ten minutes, and the average value was calculated. Both the relative permittivity (ε') and dielectric loss factor (ε") of all the samples were computed from the measured capacitance and conductivity values using equations (6) and (7).

$$\varepsilon' = \frac{\varepsilon_0}{R\sigma} C \qquad (6)$$

$$\boldsymbol{\varepsilon}'' = \frac{\sigma}{\omega\epsilon_0} \qquad (7)$$

Where, c is the capacitance of the fruit under test, ω is the angular frequency, and σ is the electrical conductivity.

The measurements were carried out between 100 kHz and 50MHz., ensuring that the plates had contact with the sample and avoided air bubbles between the plates and the material under test (Khaled *et al*., 2015). The setup for measuring the dielectric properties of fruits is presented in Figure 1.

To determine the parameters that will provide adequate penetration in the samples, equation (4) was used to evaluate the penetration of RF radiation. These frequencies were utilized to expose the fruit samples, and the resulting dielectric parameters were used for the exposure.

The proximate composition of the fruit samples was determined using the method of the Association of Official Analytical Chemists (AOAC, 2005). The moisture, carbohydrate, crude protein, fibre, ash, and fat contents of the samples were measured to ascertain the quality of the food before and after exposure to RF and microwave radiation.

To determine the shelf life of the fruits, whole fruits were exposed to varying frequencies of radiation for 10 minutes and were stored under ambient conditions in the new physics laboratory. There were six radiofrequency exposure groups with 5 MHz, 10 MHz, 15 MHz, 20 MHz, and 25 MHz. The sixth unexposed sample group served as the control. The temperature and humidity were monitored throughout the storage period until the shelf life of the fruits was exhausted. The masses of the samples were measured daily throughout the viable shelf life of the products.

RESULTS AND DISCUSSION

The analysis of conductivity variation with frequency in tomatoes, as seen in Figure 1, reveals its response to electrical fields across different frequencies. Starting at 0.36 S/m at 0.1 MHz, the specific conductivity gradually increases with frequency, peaking at 0.84 S/m at 2.5 MHz, suggesting an optimal frequency range where conductivity is maximised, possibly due to enhanced ion mobility or polarization effects. Beyond this peak, conductivity stabilizes and remains relatively constant until at higher frequencies (10 MHz and beyond), where it slightly decreases to 0.9 S/m, potentially due to reduced ion mobility or limitations in the material's response to rapid electric field changes. This highlights the frequency-dependent conductivity of tomatoes.

The variation of permittivity and loss factor with changes in frequency provides insights into how tomatoes interact with electromagnetic fields across different frequency ranges. The permittivity, values gradually decrease as the frequency increases. For instance, at lower frequencies around 0.1 MHz, the relative permittivity for tomatoes is approximately

1355.796 F/m. This value steadily decreases as the frequency increases, reaching around 3389.49 F/m at frequencies above 5 MHz. This declining trend suggests that tomatoes exhibit lower polarization and a reduced ability to store electrical energy as frequency increases. The molecules within the tomatoes may have less time to align with the alternating electric field at higher frequencies, leading to this decline in dielectric constant (Peng *et al*., 2013).

Conversely, the loss factor, which represents the energy dissipation within the material, also decreases with increasing frequency. At lower frequencies, the loss factor is quite high, as indicated by values around 60,000 at 0.1 MHz. However, as the frequency increases, this value decreases significantly, dropping to approximately 5000 at frequencies beyond 5 MHz. This diminishing loss factor implies reduced energy absorption and dissipation within tomatoes at higher frequencies, highlighting the material's ability to resist energy losses as the electromagnetic field frequency increases.

The trends in relative permittivity and loss factor in tomatoes are characteristic of dielectric materials responding to electromagnetic fields, where increasing frequency reduces energy storage and dissipation, reflecting its nature of interaction with electromagnetic waves. These frequency-dependent variations in permittivity and loss factor have significant implications for radiofrequency heating as understanding the material's frequency response is crucial for optimizing processes and minimizing energy losses. The nuanced understanding of permittivity and loss factor variations with frequency reveals how tomatoes, as dielectric materials, respond to electromagnetic fields across different frequency ranges, influenced by their molecular structure and composition, which affects their interaction with electrical fields and energy absorption characteristics.

Permittivity (ϵ') measures a material's ability to store electrical energy under an electric field, influenced by factors like water content, ion concentration, and cellular structure in tomatoes. At lower frequencies (<1 MHz), tomatoes exhibit high ϵ' (1300-3400), due to water molecules and ions aligning with the electric field. As frequency increases, molecular response time decreases, leading to a gradual decrease in ϵ'. The loss factor (ϵ") indicates energy dissipation, stemming from processes like dipole rotation, ionic conduction, and molecular relaxation. At lower frequencies, ϵ" is high, indicating significant energy absorption and dissipation, but decreases beyond 1 MHz as molecular processes become less efficient. Understanding these frequency-dependent properties is crucial for applications like radiofrequency heating, where permittivity and loss factor are crucial in optimizing processes, and non-destructive testing, where dielectric response analysis assesses moisture content, structural integrity, and quality without invasive methods (Kannan *et al*., 2013).

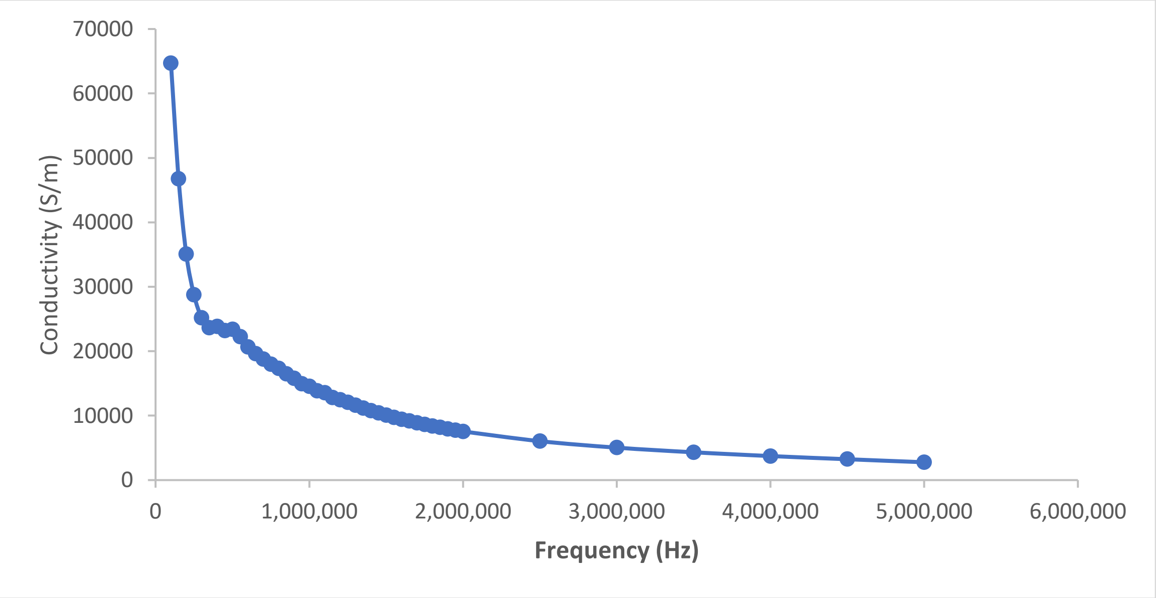

Figure 2: Variation of Electrical Conductivity with Frequency

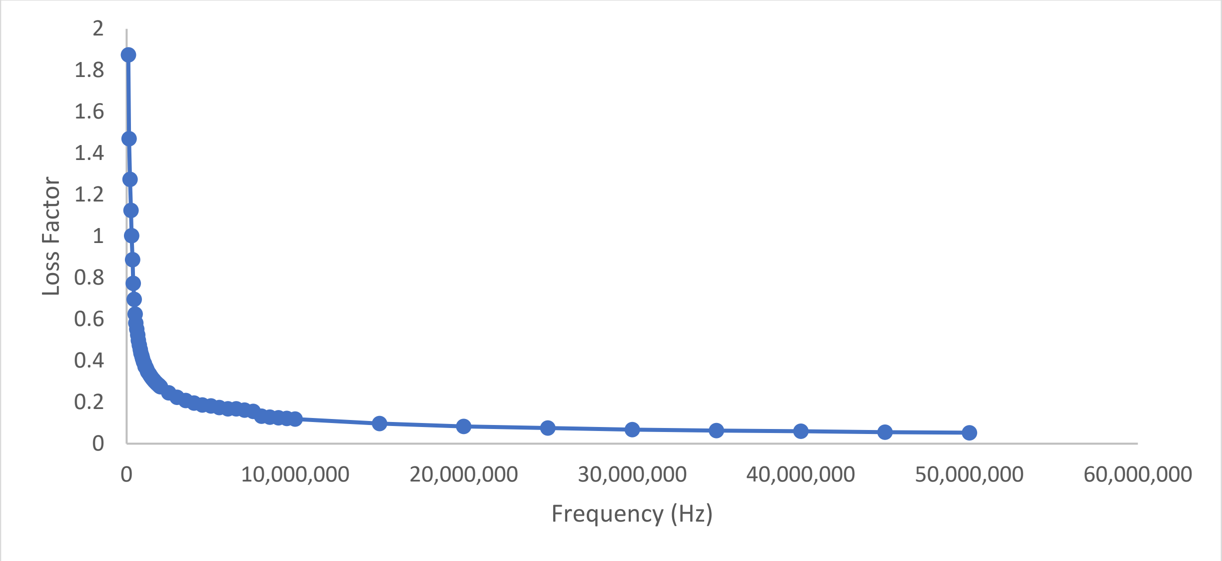

Figure 3: Variation of Loss Factor with Frequency

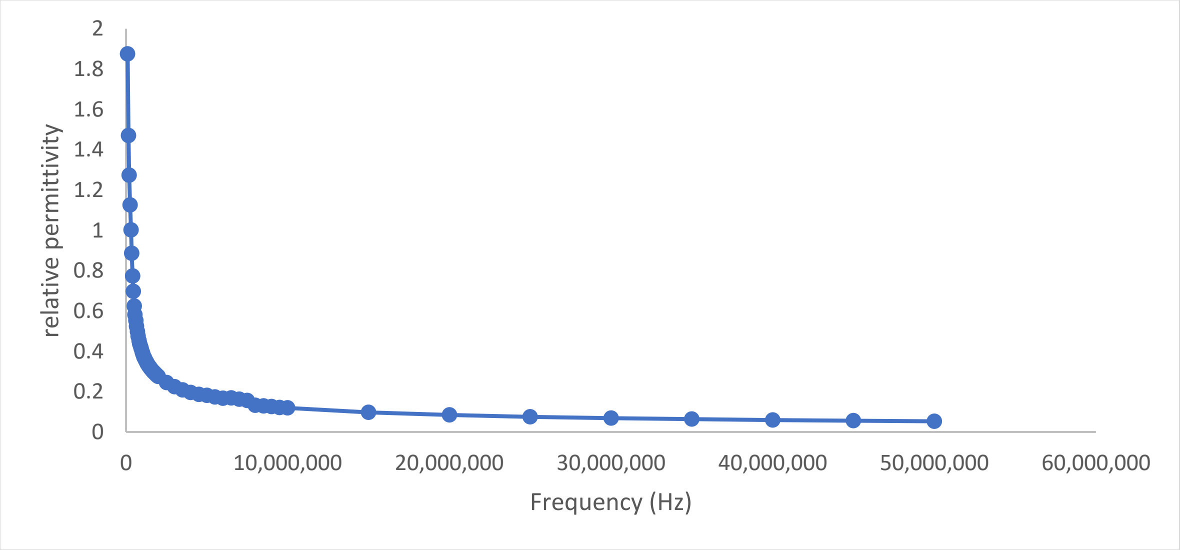

Figure 4: Variation of Relative Permittivity with Frequency

The dielectric parameters required for the radiofrequency exposure of the samples resulting in the various penetration depths were determined and have been presented. These results are shown in Table 1. The values for conductivity, specific loss factor and dielectric constant have also been presented in the table. The frequencies for exposing tomato range from 5MHz to 25MHz with a penetration depth of 0.1278m to 0.0530m as shown in Table 1.

Table 1: Exposure Parameters for Tomatoes

Frequency	σ (s/m)	ϵ'	ϵ''	Dp (m)	E (V/m)
5 MHz	0.775	2918.728	5572.68	0.127796	39.12493
10 MHz	0.776	2922.494	2789.93	0.090307	55.36669
15MHz	0.910	3427.151	2181.13	0.06809	73.43177
20 MHz	0.920	3464.812	1653.83	0.058647	85.25632
25 MHz	0.900	3389.49	1294.3	0.053035	94.27769

From Table 3, the basic parameters for preservation as regards this work are frequency and conductivity, all other parameters like dielectric constant, loss factor penetration depth and electric field depend on these two. The conductivity of tomatoes increased linearly with an increase in frequency from 0.775 to 0.920 at 5MHz to 20MHz but declined to 0.900 at 25MHz. The penetration depth however decreases with an increase in the frequency. The field intensity increased with a decrease in depth giving the fruits room for more interaction with the field. The field was allowed to interact with the fruits for 10 minutes with the hope that microbes may be destroyed, and shelf life be extended. Even though the heat generated may not kill the microbes the alternating current effect can disorient the molecular structure of the microbes by destroying some of the strands of their DNA and may lead to their death (Rosenberg *et al*., 1965). For tomatoes, its percentage water content is high and was observed after passage under an electric field to be watery and drained fast. If intended to be preserved by dryness it may not be possible but if intended for the production of tomato paste, it can serve as a means of fostering drainage of the tomatoes without excessive heating using the conventional method earlier mentioned by (Ferdous *et al*., 2017).

Some of the tomatoes did not last after exposure to the electric field for more than 14 days. Hence, tomatoes cannot be preserved for more than 14 days by this method but can be a good means to drain them into a paste.

The results for the proximate composition of the fruits are presented in Table 2.

Table 2: Proximate Composition of Tomato

Freq. (MHz)	Fat Content	Carb.	Protein	Fibre	Moisture	Ash
Control	1.030±0.030	2.627±0.452	1.467±0.029	0.197±0.015	93.789±1.415	0.225±0.013
10	0.374±0.045	5.432±1.854	1.007±0.006	0.236±0.005	92.280±2.414	0.332±0.006
15	0.336±0.004	3.905±0.702	0.964±0.032	0.140±0.036	94.757±0.175	0.232±0.008
20	0.302±0.002	4.242±0.514	0.941±0.001	0.104±0.136	94.203±0.594	0.208±0.008
25	0.414±0.018	4.601±0.678	0.933±0.001	0.061±0.004	94.078±0.120	0.265±0.333

Levene's test for homogeneity of variance was conducted for the proximate composition of tomato. All the aspects of the proximate composition were observed to vary homogenously. Hence, the One-way ANOVA test was used to test for the significance of variation in the mean proximate composition of tomato. The mean Carbohydrate ($p = 0.059$), moisture ($p = 0.254$), and ash ($p = 0.857$) content did not vary significantly from the mean of the control. Tukey's post hoc test was used to determine the irradiation groups whose mean fat, protein, and fibre proximate compositions varied significantly from the mean of the control. All the groups had no significant variation in fibre content with $p = 0.936$ for 10 MHz, $p = 0.803$ for 15 MHz, $p = 0.422$ for 20 MHz, and $p = 0.137$ for 25 MHz fibre contents. For fat content, the 10 MHz ($p = 0.032$) and 15 MHz ($p = 0.038$) had no significant variation from the control while 20 MHz ($p < 0.01$) and 25 ($p < 0.01$) varied significantly. The protein content in 10 MHz ($p = 0.028$), 15 MHz ($p = 0.027$), and 20 MHz ($p = 0.106$) did not vary significantly from the control while the 25 MHz ($p < 0.001$) varied significantly from the control.

The shelf life of tomatoes was observed to be 21 days for the control group. At this point, the 10 MHz, 15 MHz, 20 MHz, and 25 MHz samples had lost 76%, 81%, 88%, and 80% of their masses, respectively. Eventually, the shelf life of the samples was found to be 32 days for the 10 MHz and 15 MHz samples, 28 days for the 20 MHz sample and 27 days for the 25 MHz sample. Indicating 11 days increase in shelf life for the 10 and 15 MHz samples while the shelf life of the 20 MHz and 25 MHz samples was extended by 7 days and 6 days respectively. This shows an extension in shelf-life at 10 MHz and 15 MHz frequencies with a decline in shelf-life beyond 15 MHz as observed in the 20 MHz and 25 MHz samples. To assess the most effective frequencies for the radiofrequency heating of tomatoes, we compare the effect of exposure on the proximate composition and shelf life of the different sample groups.

In the tomato samples, the 10 MHz and 15 MHz frequencies both produced an extension of 11 days with no significance on the proximate composition of the samples. The 20 MHz frequency was observed to have affected the fat content significantly while the 25 MHz frequency was found to have affected the protein and fat content significantly. Hence, the 10 MHz and 15 MHz frequencies are recommended.

CONCLUSION

This study has investigated the application of radio frequency heating of tomatoes for shelf-life extension of tomatoes, grown locally in Benue State. The dielectric properties of tomatoes at radiofrequency range using the parallel plate capacitance arrangement to equally determine the effect of radiofrequency heating on the proximate composition of the tomatoes to extend its shelf life. This has been carried out at the frequency range of 10 to 50MHz while the penetration depth for effective exposure at the same frequency was found between 0.05m to 0.09m. The effect of radiofrequency on the proximate composition of Tomatoes was found to be safe for consumption at 20MHz with an extended shelf life of 11 days with no significance on the proximate composition of the samples at the field of 55.37 – 73.43V/m. The temperature rise for tomatoes was between 37° C to 39° C in 10 minutes.

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