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The Influence of Radiofrequency Heating on the Quality and Shelf of Life of Pepper

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ABSTRACT
Pepper is one of the common vegetable food items that constitute most African dishes with beneficial health properties. This study investigates the influence of radiofrequency (RF) heating on the quality and shelf life of pepper. Utilising the measured dielectric properties of pepper, the research evaluates how microwave exposure at varying frequencies affects pepper's nutritional content and preservation duration. Fresh samples of pepper were subjected to radio waves ranging from 5 MHz to 25 MHz, and their dielectric properties, proximate composition, and shelf life were analysed. The dielectric properties were measured using a parallel plate capacitance method, revealing significant variations in conductivity, dielectric constant, and loss factor across different frequencies. Results demonstrated that RF treatment effectively extended the shelf life of pepper, with the highest frequency (25 MHz) achieving a shelf life of 36 days, compared to 20 days for the control. Moreover, the study observed minimal changes in the proximate composition of pepper, ensuring the retention of its nutritional quality. This research provides valuable insights into the use of RF heating as a viable technique for extending the shelf life of pepper while maintaining its nutritional integrity.

Keywords:
Dielectric properties,
Radio wave,
Shelf life,
Proximate Composition.

INTRODUCTION

Bell Pepper (*Capsicum spp*.) is a vital horticultural crop in tropical and subtropical regions, playing a significant role in both local and global markets due to its culinary and economic value. Peppers are reported to be important sources for carotenoids, flavonoids, and vitamins responsible for fighting against ageing and prevent chronic diseases (Martínez-Zamora *et al*., 2021). Pepper has also been linked with improved cardiovascular health, hemorrhage prevention, cholesterol reduction and slowing down of ageing (Tiamiyu *et al*., 2023).

The global production of pepper is substantial, with millions of tons produced annually. For instance, in 2020, the worldwide production of green pepper was approximately 38.5 million metric tons, while the production of dry pepper was about 4.3 million metric tons. The financial returns on pepper production are notable, as the crop is not only a staple in many cuisines but also a valuable export commodity. The profitability of pepper farming varies by region and market conditions but generally provides significant income for farmers (Olutumise, 2022).

Despite its economic importance, pepper production faces challenges, especially in the post-harvest phase. Post-harvest losses can be considerable, with estimates ranging from 20% to 40% of total production, depending on handling, storage, and processing practices (Obayelu *et al*., 2021). These losses significantly impact the overall profitability and sustainability of pepper production. Addressing these challenges through improved post-harvest management practices is crucial to enhancing the economic viability of pepper cultivation.

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. (Peng *et al*., 2017). This study was conducted to assess the effect of RF heating on the shelf life and nutritional quality of pepper locally grown in Benue State, Nigeria.

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.

Biological materials are non-magnetic and their permeability μ is equal to that of free space μ_o i.e., there are no magnetic losses or absorption. Thus, the interaction of electromagnetic waves with biological materials produces electrical energy storage and absorption in the material due to the interaction of the electric field vector with the materials (Agba, 2017).

These vital electrical properties of the biological materials can be obtained from a measurement of the electrical Conductance, G (Siemens) and Capacitance, C (Farads) of the tissues (Pethig, 1979). Taken together, these two parameters define the dielectric properties of the materials. These parameters are defined by Equations (1) and (2).

$$G = k\sigma \quad (1)$$

$$C = k\varepsilon_0\varepsilon' \quad (2)$$

Where k is the measurement Cell constant, σ is the conductivity, ε' is the real part of the complex permittivity ε^* also known as the dielectric constant, and ε_0= 8.853 x 10^{12} F/m, permittivity of free space. The dielectric constant measures a material's ability to store electrical energy.

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 (3) explains the interaction of the electric field vector with biological materials. In the Debye model, molecules are considered rotating spheroids with changing orientations that vary in line with an external alternating electric field (Laogun *et al*., 1997). 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.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (3)$$

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau^2} \quad (4)$$

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1+\omega^2\tau^2} \quad (5)$$

The loss factor, $\varepsilon''$is the imaginary part of the complex permittivity and it measures the rate at which electrical energy is converted to heat, $\varepsilon_\infty$is the high-frequency permittivity, $\varepsilon_s$is the static value, ω is the angular frequency and τ, is the relaxation time (Pethig, 1979).

Penetration Depth (D_p)

Electromagnetic radiation penetration depth is an important parameter in characterizing the temperature distribution in RF-heated foods and is generally used to predict the depth that which electromagnetic 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; Tang, 2015). Equation (6) gives the depth of penetration of microwave D_p as it propagates within a material medium (Ahmed *et al*., 2007).

$$D_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\sqrt{1+(\frac{\varepsilon''}{\varepsilon'})^2-1}}} \quad (6)$$

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

The dielectric constant 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 (Eq. 6) can be rewritten as seen in Equation (7).

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

MATERIALS AND METHODS

The materials used for the study were a radiofrequency signal generator (JDS6600 DDS Signal generator/counter, USA) capacitance plates from copper material, a sample cell, a conductivity meter (Conductometer TH27 in Siemens/m) and connecting wires.

Fresh pepper samples were collected from the farm and stored at room temperature in a 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. 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 (Agba, 2017; Laogun *et al*., 1997). This region is considered for determining the appropriate plate separation for measuring the dielectric properties of the pepper samples to be tested.

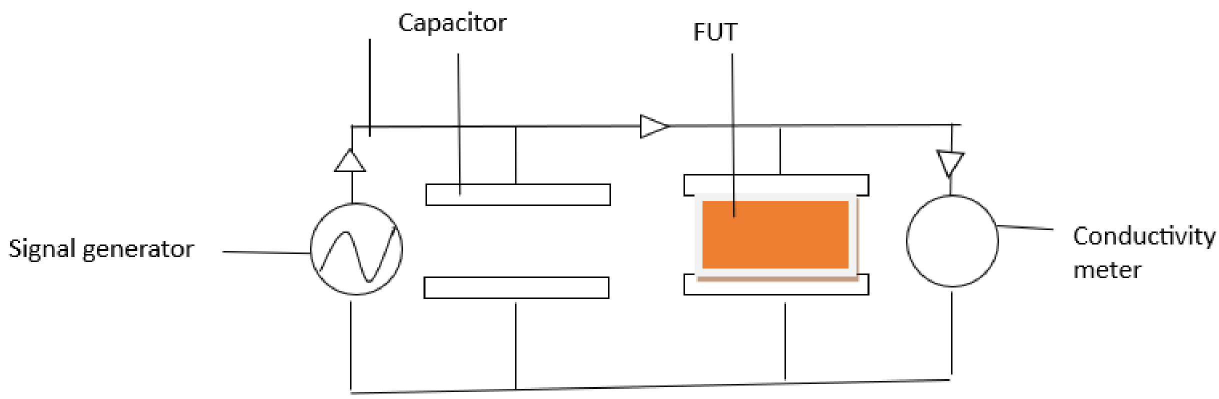

Figure 1: Circuit diagram for dielectric properties of fruits

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 at the end of timed radiofrequency irradiations. 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 (8) and (9).

$$\varepsilon' = \frac{\varepsilon_0}{R\sigma} C \quad (8)$$

$$\boldsymbol{\varepsilon}'' = \frac{\sigma}{\omega\epsilon_0} \quad (9)$$

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

To determine the parameters that will provide adequate penetration in the samples, equation (7) was used to model the penetration of RF radiation in pepper. 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 standard 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 radiofrequency 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 at the physics laboratory. There were six exposure groups with 5 MHz, 10 MHz, 15 MHz, 20 MHz, and 25 MHz frequencies of exposure. 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 pepper, as shown in Figure 2, reveals its response to electromagnetic fields across different frequencies. At 5 MHz, the specific conductivity is 0.65 S/m, indicating the material's inherent ability to conduct electricity, likely due to the presence of ions or charged particles. As frequency increases, conductivity gradually decreases to 0.35 S/m at 15 MHz, before rising to a peak at 20 MHz. This suggests an optimal frequency range where conductivity is maximized, possibly due to enhanced ion mobility or polarization effects. Beyond this peak, conductivity stabilizes and remains relatively constant until at higher frequencies (24 MHz and beyond), where it decreases to 0.33 S/m, potentially due to reduced ion mobility or limitations in the material's response to rapid electric field changes.

The specific relative permittivity of pepper, shown in Figure 3, decreases gradually with increasing frequency, indicating reduced polarization and energy storage capacity. At lower frequencies (around 5 MHz), the dielectric constant is approximately 2,447.96, but it steadily declines to around 0.35 above 15 MHz. This decrease suggests that the molecules in the pepper have less time to align with the alternating electric field at higher frequencies. Conversely, the specific loss factor, representing energy dissipation, also decreases with frequency, dropping from 2336.929 at 5 MHz to approximately 174 beyond 28 MHz. This reduction implies that pepper resists energy losses as the electromagnetic field frequency increases, with lower energy absorption and dissipation.

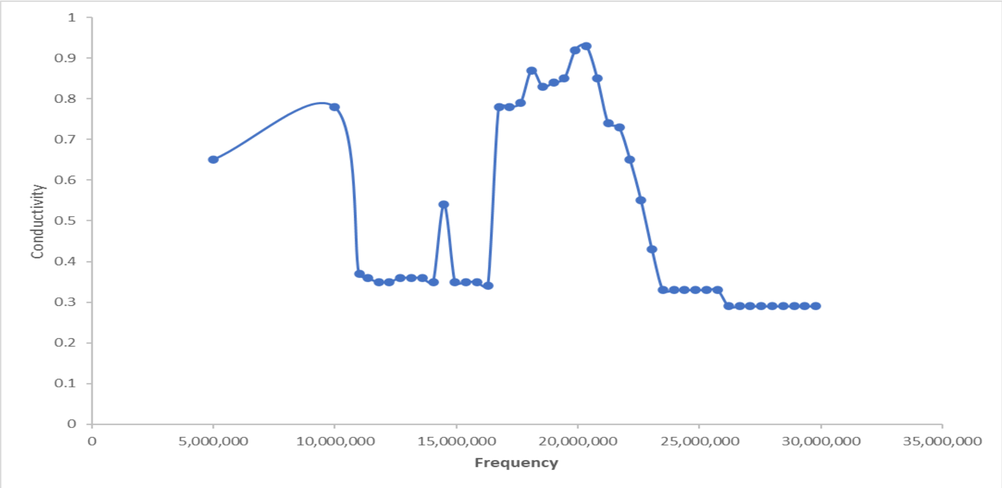

Figure 2: Variation of Electrical Conductivity with Frequency

The trends in dielectric constant and loss factor in pepper are characteristic of dielectric materials responding to electromagnetic fields, with decreasing energy storage and dissipation abilities as frequency rises, reflecting a more efficient interaction with electromagnetic waves. These variations have practical implications in radiofrequency heating, sensor design, and device development, where understanding the material's frequency response is crucial. The permittivity and loss factor variations are rooted in pepper's molecular structure and composition, influencing its interaction with electrical fields and energy absorption. The dielectric constant, representing a material's ability to store electrical energy, is influenced by factors like water content, ion concentration, and cellular structure (Içier & Baysal, 2004). At lower frequencies (<5 MHz), pepper's high specific dielectric constant (2447.965-3163.52) is attributed to water molecules and ions aligning with the electric field. As frequency increases, the molecular response time decreases, leading to a gradual decline in permittivity. At higher frequencies, pepper's molecular and structural characteristics dominate its dielectric response, highlighting the importance of understanding these properties for applications across a wide frequency spectrum. As the frequency increases, however, the molecules within the pepper, including water and ions, have less time to respond to the alternating electric field. This reduced response leads to a gradual decrease in the relative permittivity with increasing frequency. Additionally, the cellular structure of pepper, composed of various organic compounds and membranes, also influences permittivity. At higher frequencies, the material's molecular and structural characteristics likely play a more dominant role in determining its dielectric response (Bei *et al*., 2017).

The loss factor (ε") (Figure 4), indicates energy dissipation within pepper when subjected to an electric field, complementing the dielectric constant. Energy dissipation in pepper like other biomolecules, stems from processes like dipole rotation, ionic conduction, and molecular relaxation (Laogun *et al.*, 1997). At lower frequencies, the loss factor is relatively high, indicating significant energy absorption and dissipation. However, beyond 1 MHz, the loss factor decreases notably, signifying reduced energy absorption and dissipation at higher frequencies. This decrease occurs because molecular processes like dipole rotation and ionic conduction become less pronounced or efficient, and reduced time is available for molecular reorientation or relaxation, contributing to lower energy losses at higher frequencies.

Understanding the frequency-dependent properties of pepper is vital for various applications, including food processing, agriculture, and quality control. Knowledge of permittivity and loss factor enables optimization of radiofrequency and microwave heating processes, leveraging higher permittivity at lower frequencies for efficient energy absorption and minimizing energy wastage with lower loss factors at higher frequencies for precise heating control. Additionally, analyzing the dielectric response of peppers at different frequencies allows for non-destructive testing and sensing in agricultural and quality control applications, enabling assessment of moisture content, structural integrity, and overall quality without invasive methods, and paving the way for innovative applications in food processing and quality control(El-Mesery *et al*., 2019).

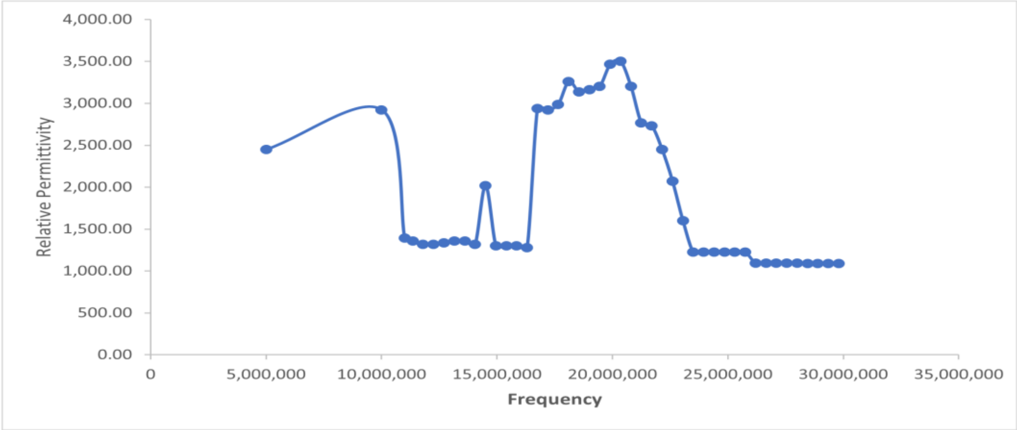

Figure 3: Variation of Relative Permittivity with Frequency

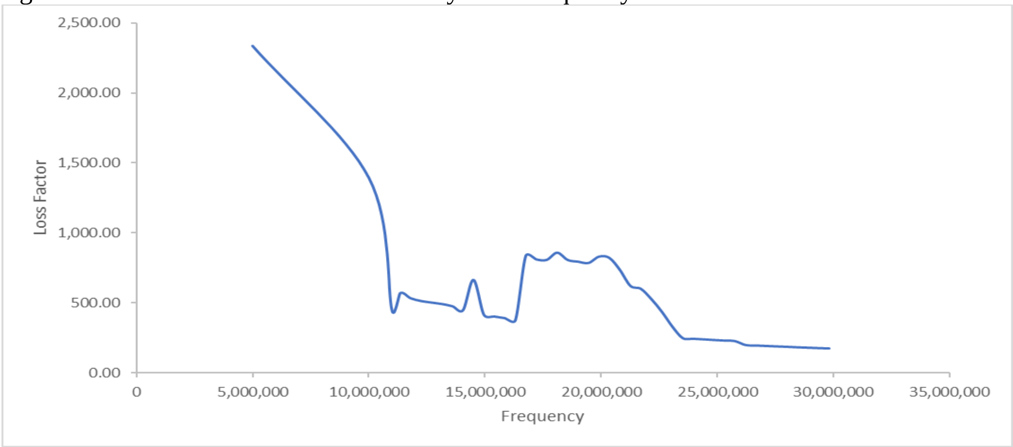

Figure 4: Variation of dielectric loss factor with frequency

The dielectric parameters required for the exposure of pepper samples resulting in the right penetration depth were determined and have been presented in Table 1. The values for conductivity, specific loss factor and dielectric constant have also been recorded. The penetration depth for Pepper was observed to range from 0.0593 m (5.93 cm) to 0.1209 m (12.09 cm) within the 5 MHz to 25 MHz range.

Table 1: Exposure Parameters for Pepper

Frequency	**σ(S/m)**	**ϵ'**	**ϵ''**	**Dp** (m)	**E (V/m)**
5 MHz	0.865	3257.677	6219.83	0.120965	41.33431
10 MHz	0.776	2922.494	2789.93	0.090307	55.36669
15 MHz	0.757	2850.938	1814.42	0.074655	66.97477
20 MHz	0.724	2726.656	1301.49	0.06611	75.63137
25 MHz	0.721	2715.358	1036.88	0.059254	84.38307

The shelf life for pepper was observed to be 20 days for the control sample, 25 days for the 10 MHz sample, 30 days for the 15 MHz sample, and 36 days for the 20 MHz and 25 MHz samples, indicating an extension in their shelf life by 16 days in the 20 MHz and 25 MHz groups, 10 days in the 15 MHz group, and 5 days in the 10 MHz group. The 10 MHz, 15 MHz, 20 MHz, and 25 MHz samples had 5.8%, 9.9%, 13%, and 6.5% of their initial mass remaining after the control samples had gone bad. A decline in shelf life with increasing frequency is observed, indicating a threshold frequency beyond which there is a decline in the shelf life of radio wave-irradiated pepper samples. This may be attributed to the differential heating effect and varied depth of penetration by the waves in these samples, resulting in varying levels of microbial inactivation that consequently impact the shelf life of these products. Cathcart *et al*., (1947) have previously reported the use of radiofrequency radiation for food pasteurization with exposure leading to the elimination of fungal load even after ten days of storage. Also, another study reported the ability of RF to control both *Aspergillus* and

Penicillium in sliced bread when treated at 26 MHz (Weston & Barth, 1997)

The result of the proximate analysis is presented in Table 2 below. The result discusses and compares the variation of the irradiated samples to the unirradiated control. Levene's test revealed homogeneous variance in mean fat and protein compositions, but heterogeneous variance in carbohydrate, fibre, moisture, and ash contents of pepper. One-way ANOVA showed significant variation in Levene's test revealed homogeneous variance in mean fat and protein compositions, but heterogeneous variance in carbohydrate, fibre, moisture, and ash contents of pepper. One-way ANOVA showed significant variation in fat and protein content, with Tukey's post hoc test indicating all irradiated samples varied significantly from the control ($p < 0.001$). Welch's ANOVA revealed significant variation in carbohydrate, fibre, moisture, and ash contents from the control ($p < 0.001$). Games-Howell post hoc test showed significant variations in carbohydrate content at 15 MHz ($p < 0.001$), fibre content at 10 MHz ($p = 0.0001$), 15 MHz ($p = 0.0009$), and 25 MHz ($p = 0.0170$), moisture content at 10 MHz ($p = 0.001$), and ash content at 10 MHz ($p < 0.001$) and 15 MHz ($p < 0.001$), while other frequencies showed no significant variation from the control. fat and protein content, with Tukey's post hoc test indicating all irradiated samples varied significantly from the control ($p < 0.001$). Welch's ANOVA revealed significant variation in carbohydrate, fibre, moisture, and ash contents from the control ($p < 0.001$). Games-Howell post hoc test showed significant variations in carbohydrate content at 15 MHz ($p < 0.001$), fibre content at 10 MHz ($p = 0.0001$), 15 MHz ($p = 0.0009$), and 25 MHz ($p = 0.0170$), moisture content at 10 MHz ($p = 0.001$), and ash content at 10 MHz ($p < 0.001$) and 15 MHz ($p < 0.001$), while other frequencies showed no significant variation from the control.

Table 2: Proximate Composition of Pepper

Freq.	Fat content	Carb.	Protein	Fibre	Moisture	Ash
Control	1.007±0.005	15.319±0.132	1.000±0.000	0.005±0.001	82.408±0.132	0.262±0.003
10 MHz	0.828±0.001	13.526±0.222	0.730±0.017	0.011±0.000	84.437±0.188	0.597±0.008
15 MHz	0.641±0.001	12.106±0.163	0.713±0.015	0.601±0.002	82.668±0.153	3.270±0.054
20 MHz	0.650±0.010	17.138±0.003	0.723±0.015	0.022±0.029	81.185±0.020	0.282±0.008
25 MHz	0.636±0.001	16.932±0.015	0.737±0.012	0.003±0.000	81.363±0.019	0.328±0.008

A summary of the results of significance in variation in the proximate composition of pepper is presented in Table 3.

Table 3: Significance in Variation of Mean Proximate Composition of Pepper

	Proximate Composition					
Frequency	**Ash**	**Fibre**	**Moisture**	**Protein**	**Carbohydrate**	**Fat**
10 MHz	Sig	Sig	Sig	Sig	NS	Sig
15 MHz	Sig	Sig	NS	Sig	Sig	Sig
20 MHz	NS	NS	NS	Sig	NS	Sig
25 MHz	NS	Sig	NS	Sig	NS	Sig

To assess the most effective frequencies for the different frequencies, we compared the effect of exposure on the proximate composition and shelf life of the different sample groups.

The 20 MHz and 25 MHz irradiations are observed to produce the highest extension in shelf life by 16 days, though they have effects on the proximate composition of the samples compared to the control. The protein and fat contents in the 20 MHz group varied significantly from the control, while fibre, fat, and protein varied significantly in the 25 MHz group. The 10 MHz and 15 MHz irradiations also extended the shelf life by 10 and 5 days, respectively, but only the variation in carbohydrate content was found to be insignificant for the 10 MHz irradiation, and only the moisture content variation in the 15 MHz group was insignificant. The results show a frequency-dependent increase in the shelf life of pepper, with the 20 MHz sample showing a higher extension in shelf life with minimal impact on the aspects of proximate composition. Hence, the 20 MHz frequency is recommended for radiofrequency heating of pepper for preservation.

CONCLUSION

This study has investigated the application of radio waves in the shelf-life extension of pepper, grown locally in Benue State. Between 5 MHz and 50 MHz, the electrical conductivity of pepper was found to range between 0.34 S/m to 0.93 S/m, the dielectric constant was between 1088.40 to 3502.47, and the dielectric loss factor was between 2336.92 to 174.33 and 20 MHz is the recommended radio frequency for dielectric heating of pepper.

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