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RESEARCH ARTICLE

Dielectric spectrum of ripe papaya and navel orange fruit juices from 1 to 50 GHz using time domain reflectometry

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Abstract

This paper investigates the complex dielectric properties, consisting of the real part, i.e., dielectric constant (ε') and the imaginary part, i.e., dielectric loss (ε''), of ripe papaya and navel orange fruit juices utilise the time domain reflectometry (TDR) technique. Filling a significant gap in existing literature, the study focuses on fruit juice complex dielectric properties measurement within the frequency (f) range 1GHz ≤ f ≤ 50 GHz to know the frequency dependence variation. Experimental measurements were conducted at 23 °C using fruit samples processed into filtered juices. The ε'-f curves reveal distinct dielectric behaviours between papaya and orange juices. Papaya exhibited significantly higher ε' up to 18 GHz, but this trend reversed thereafter. Similar opposing behaviors were observed in the ε''-f curves. Both juices displayed relaxation frequencies, with papaya peaking at 8 GHz and orange at 10.5 GHz. The study has the potential to advance food processing procedures, boost product standards and stimulate innovation across several sectors.

Keywords: dielectric spectrum; food industries; fruit juices; time domain reflectometry

Introduction

Knowledge of the complex dielectric constant holds profound significance as it conveys crucial insights into the interaction between materials and electromagnetic fields. The real part, the dielectric constant (ε'), of the complex dielectric constant represents a material's ability to store energy when subjected to an electric field. This part contributes to our understanding of processes such as polarisation and the creation of electric dipoles within the material. The imaginary part, the dielectric loss factor (ε''), the imaginary portion of the complex dielectric constant, determines the amount of energy absorbed and dissipated within the material. It demonstrates how electromagnetic waves are attenuated when they pass through a material due to phenomena such as molecule movement and electron mobility (1, 2). Together, these aspects of the complex dielectric constant provide an in-depth understanding of how materials influence electromagnetic wave behaviour. The complex dielectric constant (ε*) of a material relative to that of free space is given by equation 1.

$$\varepsilon^* = \varepsilon' - j\,\varepsilon'' \qquad \text{(Eqn .1)}$$

Where ε' is the real part, ε'' is the imaginary part and j=√(-1). The ratio of the imaginary part to the real part of the complex dielectric constant is called the loss tangent (tanδ) and is given by equation 2.

$$\tan\delta = k''/k' = \varepsilon''/\varepsilon' \qquad \text{(Eqn .2)}$$

Where, k' is the relative dielectric constant and k'' is the relative dielectric loss, k' = ε'/ε0 and k'' = ε''/ε0 and ε0 is the permittivity of free space and its value is 8.854 × 10-12 Fm-1.

The dielectric properties of materials are subject to influence from factors like frequency, temperature and moisture content. Notably, these properties exhibit significant variations with changes in frequency, providing crucial insights into the material's characteristics. The dielectric characteristics of a substance are significantly affected by temperature. Typically, at lower frequencies, the loss factor increases with temperature due to increased ionic conductance, whereas at higher frequencies, it decreases as temperature rises. Most materials contain moisture, which typically correlates with higher dielectric constants and loss factors (3).

Experiments by various researchers have been conducted to investigate the complex dielectric properties in various domains of food items, including vegetables, fruits and fruit juices at different frequencies and temperatures. In the domain of fruit juices, researchers engaged in complex dielectric fruit juice studies at different frequencies and temperatures as discussed subsequently.

In previous studies, a novel method for assessing juice dielectric properties across microwave frequencies. By comparing fresh and packed juices, it demonstrates the potential for quality control. The technique is simple, quick and applicable to various juices (4).

The determination of sugar content in 10 matured red seedless watermelons through dielectric property measurements were reported previously (5). Comparisons between watermelon juice and sugar-water mixtures are made across a frequency range of 200 MHz to 20 GHz. Results suggest a strong correlation between dielectric properties and sugar content, aiding in predicting sugar levels. Additionally, the study includes high-performance liquid chromatography (HPLC) measurements for standard sugar content verification and graphical representations illustrate the relationships between dielectric measurements of watermelon juice and sugar-water mixtures (5).

Another study explores the dielectric properties of fruit juices across frequencies 1 to 25 GHz, crucial for optimising microwave processing and ensuring product quality. Various juices like pomegranate, sweet lime and lemon were analysed. Dielectric measurements revealed frequency-dependent behaviour, attributed to molecular structure and polarisation (6).

Previous researchers, examine the complex permittivity of fresh juice from 2 grape cultivars, Sultania (green grapes) and Black Monukka (black grapes), across frequencies from 1 to 50 GHz and temperatures from 30 to 60 °C. Utilise a PNA network analyser and coaxial probe, it predicts relaxation frequencies for the 2 cultivars based on Cole-Cole plots and regression lines. The results highlight the influence of grape acidity and sugar content on dielectric properties, indicating differing molecular structures between cultivars (7).

The dielectric properties of litchi fruit using the open-ended coaxial probe method across frequencies (0.5 to 20 GHz) and storage times were reported earlier. Results show variations in temperature and frequency, informing potential applications like microwave-assisted drying and quality sensing (8).

Previous researchers have made major advances in understanding the dielectric behaviour of fruit juices at frequencies lower than 3 GHz (9–15).

The measurement of fruit juice complex dielectric properties at microwave frequencies is crucial for optimising processing techniques such as pasteurisation, sterilisation and drying. These techniques heavily rely on the ability of microwaves to penetrate and heat food materials, including fruit juices, efficiently and uniformly. Accurate measurements of dielectric properties enable the precise control of microwave energy, ensuring desired outcomes such as microbial inactivation, preservation of nutritional content and sensory attributes in fruit juice products.

In comparison, dielectric properties measurements below 3 GHz primarily serve the purpose of evaluating fruit juice quality and refining manufacturing processes to ensure consistency and efficiency. Specifically, dielectric constant measurements at lower frequencies, such as determining sugar content in fruit juice by analysing changes in dielectric constant, are integral. This aids in quality assessment and monitoring of ripening processes, ensuring consistency and flavour profile. Additionally, dielectric loss measurements in this range, like assessing the conductivity of fruit juice to detect impurities or changes in electrolyte concentration, play a crucial role in process optimisation for maintaining desired conductivity levels and ensuring product safety.

On the other hand, within the 1 to 50 GHz range, dielectric measurements offer a more intricate analysis due to heightened sensitivity to the molecular structure of the juice. This extended frequency range enables advanced quality assessment techniques, such as investigating subtle changes in molecular structure and composition, indicative of spoilage or adulteration. For instance, examining the mobility of water molecules and other constituents in fruit juice at elevated frequencies allows for fine-tuning microwave processing parameters for optimal preservation and flavor retention. Consequently, while sub-3 GHz measurements prioritise fundamental quality control, the 1 to 50 GHz range facilitates more sophisticated analysis and optimisation possibilities for fruit juice processing.

The existing literature lacks sufficient research on the complex dielectric properties of fruit juices within the frequency range of 1 to 50 GHz. Specifically, scarcity of data about the dielectric constants of ripe papaya and navel orange juices across this frequency spectrum. Therefore, this paper aims to address this gap by conducting experimental measurements of the complex dielectric constants of ripe papaya and navel orange juices across the frequency range of 1 to 50 GHz, at 23 °C.

Materials and Methods

Navel oranges (*Citrus sinensis* (L.) Osbeck) are renowned for their delectably sweet, tangy flavour and succulent texture. Extracted from these oranges, navel orange juice presents as a revitalising and nutrient-rich beverage, offering hydration and a wealth of vitamins, minerals and antioxidants. Its appealing taste profile and nutritional richness render it a favoured choice for consumption in its pure form or as an ingredient in diverse culinary concoctions.

Papaya (*Carica papaya* L.) juice, like numerous fruit juices, boasts a bounty of nutrients and bioactive compounds. This refreshing beverage not only hydrates but also provides a spectrum of essential vitamins, minerals, antioxidants and enzymes. Revered for its revitalising flavour and potential therapeutic properties, papaya juice is cherished for its myriad health benefits, appealing to a broad audience seeking both taste satisfaction and wellness enhancement.

These 2 fruit juices were chosen for experimental trials due to their widespread consumption and perceived health benefits. Furthermore, as previously indicated, there is a notable lack of comprehensive research reports addressing the measurement of the complex dielectric properties of these fruit juices within the frequency range of 1 to 50 GHz. The experiment utilised fresh oranges of the 'Navelina' variety as this is widely used as intake and easily available and ripe papayas of ‘red lady’ as this variety mostly cultivated in the region.

Fruits were procured from a nearby supermarket, ensuring that only those at the ripe stage were selected through visual observation. These fruits underwent slicing and their juice was extracted using a juicer grinder. Subsequently, the extracted orange juice underwent filtration by using ordinary filter paper of pore size 20 to 25 µm to eliminate any pulp and the papaya by using filter paper of pore size almost 10 µm. This filtered juice is then utilised as study samples. Time domain reflectometry (TDR) is used to determine the complex dielectric constant.

The TDR stands out as an invaluable technique for examining how materials interact with electromagnetic waves over time (16). By providing precise measurements of wave propagation, TDR allows for a detailed understanding of the material's behaviour across varying frequencies. Its application in dielectric studies not only offers dynamic real-time analysis but also facilitates the exploration of complex electromagnetic interactions within the material structure.

The frequency-dependent complex dielectric properties of navel orange and ripe papaya juice were analysed within the range of 1 to 50 GHz at 23 °C. Utilise a Tektronix digital serial analyser DSA 8300 with a dual-channel sampling module 80E10B, equipped with a tunnel diode generating a 12 ps incident and 15 ps reflected rise time pulse, transmitted through a coaxial cable of 50-ohm impedance, with inner and outer diameters of 0.28 mm and 1.19 mm, respectively. The sampling oscilloscope captured changes in pulse reflection from the cable's end, recording both the pulse without the sample R1(t) and with the sample Rx(t) within a 5 ns time window, digitised into 2000 points. The subtraction q(t) = R1 (t) - Rx(t) and addition p(t) = R1(t) + Rx(t) of these pulses were stored in the oscilloscope's memory. The Fourier transformation converted the time domain data into frequency domain data within the specified frequency range. The TDR calibration followed manufacturer guidelines and utilised solvents of known dielectric constants. The experimental setup, illustrated in Fig. 1 and shown in Fig. 2. The Fourier transformation was applied to both pulses, followed by thorough data analysis using a non-linear least square fit method (16, 17), aiming to determine the complex permittivity spectra. This method is already used for biological materials (18). The complex dielectric spectra have been obtained by using the Havriliak-Negami equation (3).

$$\varepsilon^* = \varepsilon_\infty + \frac{(\varepsilon_0 - \varepsilon_\infty)}{(1 + (j\omega\tau)^{1-\alpha})^\beta} \qquad \text{(Eqn .3)}$$

where ε_0 represents static dielectric permittivity,

ε_∞ denotes permittivity at high frequency,

τ signifies relaxation time and α and β are distribution parameters.

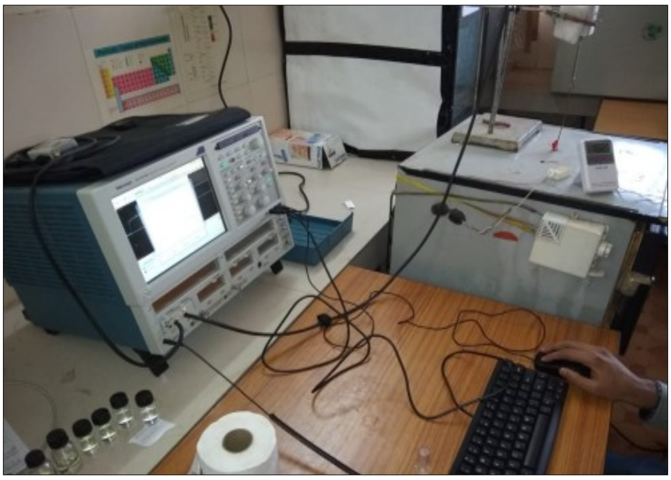

Fig. 2. Experimental set up of time domain reflectometry.

The equation encompasses Cole-Cole (β = 1), Cole-Davidson (α = 0) and Debye (α = 0 & β = 1) relaxation models, with the Debye model employed for data fitting.

Results and Discussion

Fig. 3 depicts the dielectric constant (ε')–frequency (f) curves for navel orange and ripe papaya juices from 1 to 50 GHz at 23 °C. The nature of curves shows how the dielectric constant ε' changes for navel orange and papaya juice at a temperature of 23 °C over a frequency spectrum of 1 to 50 GHz. With increased frequency, a steady decline in ε' is seen. Interestingly, both juices show an intersecting point on the diagram at about 18 GHz. Before this intersection, papaya juice has a higher dielectric constant than orange juice, with an average difference of 9 magnitudes. The papaya juice has a higher dielectric constant at 1 GHz microwave frequency compared to orange juice due to its higher water content. Therefore, the dielectric responses of papaya are an observation on other high-moisture biological materials and fruits,

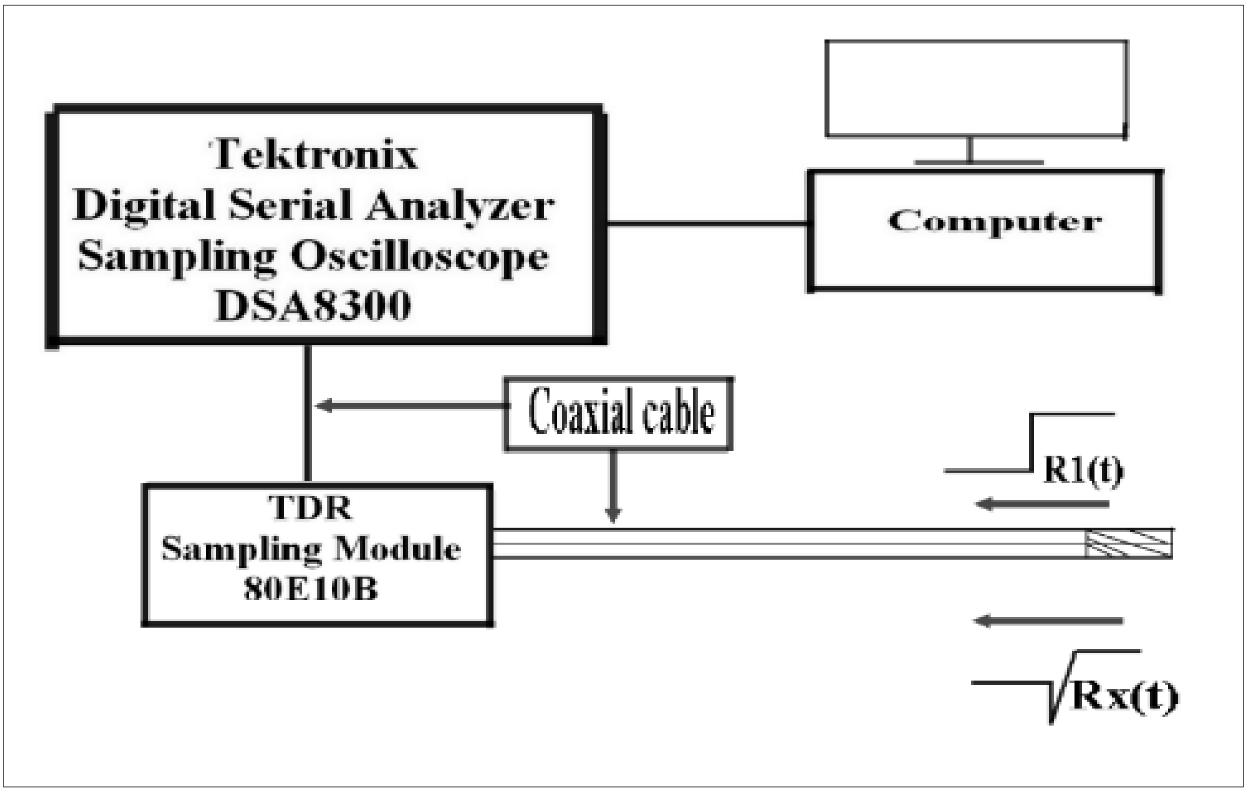

Fig. 1. Block diagram of an experimental set of time domain reflectometer.

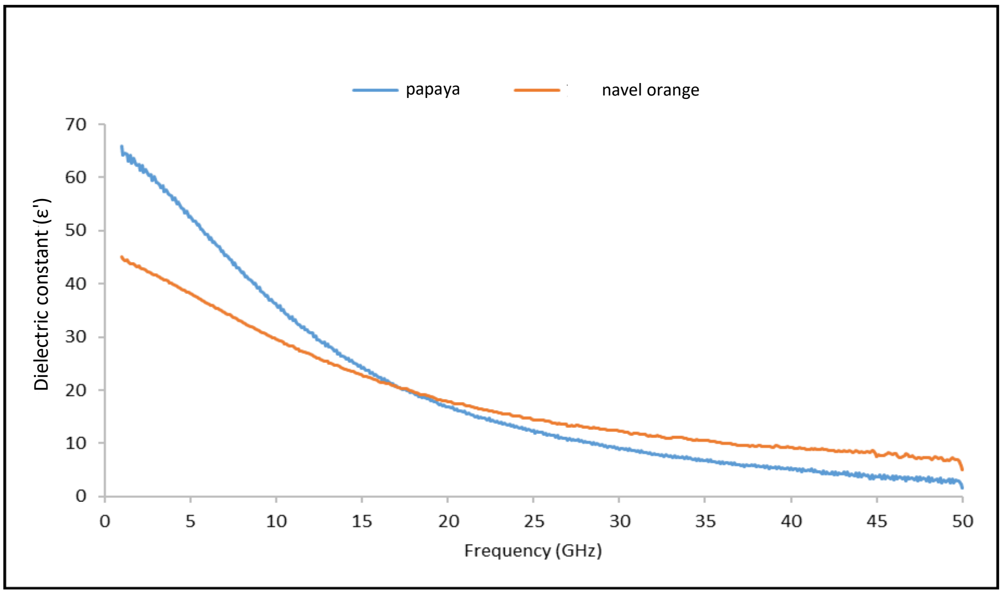

Fig. 3. The dielectric constant (ε')–frequency (f) curves for navel orange and ripe papaya juices from 1 GHz to 50 GHz at 23 °C.

implying an influence of the internal water structure and mobility of ions on dielectric characteristics. It is said to be due to the relatively free or loosely bound water molecules amongst those which largely contribute in enhancing dipolar and interfacial polarisation effects reported by previous researchers (19, 20).

However, as the frequency gets closer to 18 GHz, the difference gets smaller very quickly. Following the intersection frequency i.e., from 18 to 50 GHz, orange juice's dielectric constant typically exceeds papaya juice's by an average of 3 magnitudes.

Fig. 4 depicts the dielectric loss (ε'') -frequency (f) curves for navel orange and ripe papaya juices from 1 to 50 GHz at 23°C. The ε''-f curve starts from a minimum at approximately 1.0 GHz. Subsequently, ε'' increases with frequency, reaching a maximum at about 10.5 GHz for navel orange juice and 8 GHz for ripe papaya juice, likely due to the relaxation frequency. When an alternating electric field is applied to fruit juice, the polar molecules strive to align with the field. At low frequencies, these molecules can align and realign with the oscillating field. However, as the frequency increases, a point is reached where the molecules can no longer reorient quickly enough to keep pace with the field, known as the relaxation frequency. Beyond this frequency, ε'' decreases with increasing frequency and rapid oscillations are observed in the frequency range above 45 GHz. Papaya and orange fruit are low salt content fruit. The low salts present in this juice can interact with water molecules and other dissolved substances, causing changes in molecular configurations and dynamics. These interactions can lead to observable rapid oscillations observed in ε'' at this frequency range. Furthermore, papaya juice is not a homogeneous solution but a complex mixture comprising various components, including water, sugar, proteins, fibres and other organic molecules. These constituents possess differing complex dielectric properties and their interactions may have contributed to irregularities ("Not-so-smooth") in the complex dielectric spectra, as depicted in Fig. 3 and 4.

Conclusion

The complex dielectric characteristics of ripe papaya and navel orange juices at frequencies ranging from 1 to 50 GHz and at 23 °C were measured using time domain reflectometry (TDR). The ε'-f curve shows that papaya and orange juices have distinct dielectric behaviours. At frequencies, papaya juice had a greater dielectric

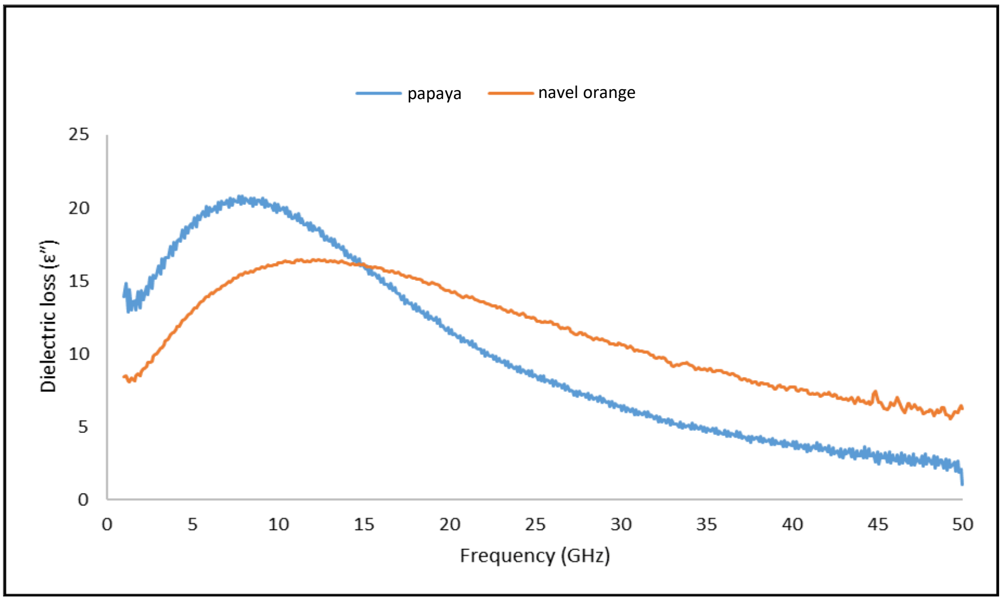

Fig. 4. The dielectric loss (ε'')–frequency (f) curves for navel orange and ripe papaya juices from 1 GHz to 50 GHz at 23 °C.

constant than orange juice by an average of 9 magnitudes. However, after the intersection at 18 GHz, the opposite behaviour in is seen. Similarly, in the ε''-f curve, opposite behaviour in ε'' on two sides of the intersection is observed. Both juices exhibited a relaxation frequency, with navel orange juice peaking at approximately 10.5 GHz and ripe papaya juice at 8 GHz. Future research ought to investigate into other factors that influence dielectric properties, such as temperature variations, juices from fruits at different stages of ripeness, packaged and natural juices and the effects of various processing processes. This study would improve our understanding and optimisation of fruit juice manufacturing processes.

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Authors' contributions

ABI coordinated the study, including literature survey, research design, sample selection, measurements and calculations and preparation and analysis of data. ABI also participated in writing the manuscript. ASJ was involved in data preparation, analysis and interpretation. ARD carried out measurements of the samples using time domain reflectometry and calculated the dielectric constant and loss from the raw data. ACK provided access to the experimental setup and mentored the overall research. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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