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Dielectric Properties of Beetroot Juice: Temperature and Frequency Dependence

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ABSTRACT

Beetroot is a nutritious vegetable that is high in vitamins and minerals. Beetroot is a source of abundant in antioxidants and minerals, including vitamin C, sodium, potassium, betaine, and magnesium. This study investigates the dependence of dielectric properties of beetroot juice on temperature and frequency, focusing on its dielectric constant and loss factor. The dielectric properties of fresh beetroot juice were evaluated using an open-ended coaxial probe method. Dielectric properties are related to the capacitive properties of materials. Dielectric constant of the sample is decreasing with frequency and temperature, while dielectric loss is increasing with frequency and temperature. The results highlight the influence of molecular dynamics on energy storage and dissipation, offering insights relevant to microwave-assisted food processing.

1. Introduction

The taproot part of the plant is called the beetroot. Red beetroot is rich in minerals, including iron, copper, potassium, sodium, manganese, and magnesium [1]. Beetroot has several medicinal applications and can help prevent heart disease and some cancers, including colon cancer [2]. With a pH 7.5 - 8, beetroot is an alkaline meal that is high in vitamin C, vitamin B1, B2, niacin, vitamins B6, and B12. Its leaves are also a great source of vitamin A.

The dielectric characteristics of different biological materials and agri-foods are being used increasingly as new and rapid technologies are developed for usage in their respective sectors and research labs. Knowledge of a material's dielectric characteristics is crucial in a variety of domains, including material engineering, food science, and agriculture, especially when considering different microwave frequencies and temperatures. The dielectric properties of beetroot, which include parameters like the dielectric constant and dielectric loss, can provide valuable insights into its behaviour under different conditions. The interaction between electromagnetic radiation and matter is characterized by fundamental parameters known as dielectric properties. These properties play a crucial role in determining and developing applications of materials based on their electrical characteristics. By studying the dielectric data of materials, valuable insights can be gained to effectively understand their capacitive properties, energy storage capabilities, and energy losses resulting from their interaction with electromagnetic fields. In food science, dielectric properties are essential for achieving uniform heating, accurate moisture content analysis, and effective quality control during microwave processing. For microwave applications, these properties enable the efficient design of heating systems, ensuring precise energy absorption and enhancing processes such as drying, sterilization, and material analysis.

The dielectric permittivity of materials at microwave frequencies can be represented as a complex number, $\varepsilon^* = \varepsilon' - j\varepsilon''$, where ε' is the real part, which is known as the dielectric constant, and ε'' is the imaginary part, referred to as the dielectric loss factor [3]. Dielectric constant (ε') is the ratio of the material's electrical permittivity to the free space permittivity. The dielectric constant characterizes the material's ability to store electromagnetic energy and is a molecular property that is dependent on temperature and frequency and it also depends on the material's internal structure. The dielectric constant's value is essential in determining how electromagnetic energy is reflected and transmitted when it encounters the interface between material and air [4]. In the case of a vacuum, the dielectric constant is simply equal to one ($\varepsilon'=1$).

The dielectric loss factor (ε'') is a measure of how well a material can convert electromagnetic energy into heat [5], and it depends on both the frequency and the specific dielectric material. The complete spectra of dielectric loss factor (ε'') of high water-content food exhibit an intricate interplay between the fluctuation of molecular dipoles and the loss mechanisms of ionic conduction. These mechanisms manifest with varying degrees of intensity as the frequency changes. It can be expressed mathematically as $\varepsilon'' = \varepsilon''_\sigma + \varepsilon''_d$; where ε''_σ is a dielectric loss because of ionic conduction and ε''_d is a loss because of dipole rotation.

The assessment of dielectric permittivity in beetroot juice at microwave frequencies represents a specialized methodology aimed at elucidating the dielectric characteristics of this juice. This examination provides essential insights into how fruit juice behaves in microwave settings, offering valuable data on its interaction with electromagnetic fields [6]. Such comprehension is pivotal for diverse applications, including enhancing food processing techniques, advancing product development, and conducting quality evaluations.

2. Experimental Methods

2.1 Sample Preparation

To perform the experimental investigation, a freshly obtained sample of beetroot was acquired from a nearby local supermarket, and juice was extracted using a centrifugal juicer and strained with the help of a filter approx a pore size of 60 µm to remove any particulate matter, and impurities, maintaining the purity of the sample.

2.2 Method

The dielectric constant and dielectric loss factor of the fresh beetroot juice were measured using a high-frequency vector network analyzer, model Agilent E8364C, in the frequency range of 1 GHz to 20 GHz at different temperatures 25 °C to 55 °C.

The study utilized an open-ended coaxial probe system to evaluate the dielectric properties of materials by analysing signal reflection and transmission at the sample interface. Measurements of S-parameters at various frequencies provided insights into the material's permittivity and permeability. Calibration ensured accuracy, and S-parameters provided data to calculate the dielectric constant and loss using software integrated with a vector network analyser.

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Fig. 1 PNA Network Analyzer with 85070E dielectric probe kit

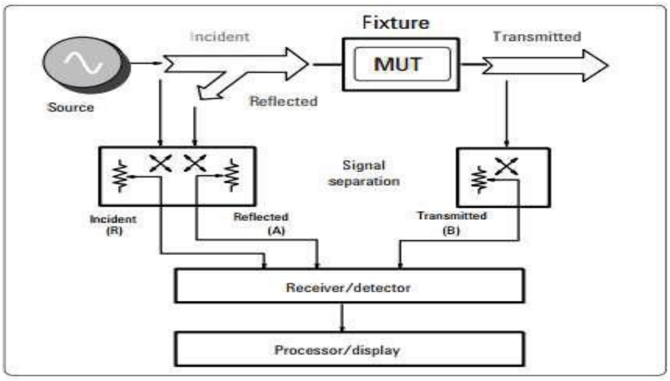

Fig. 2 Network analyzer flow diagram

3. Results and Discussion

In the current study, the dielectric constant (ε′) and dielectric loss (ε′′) at various frequencies (1 GHz to 20 GHZ) and four distinct temperatures: 25 °C, 35 °C, 45 °C, and 55 °C were measured. The recorded results, in Figs. 3 and 4, illustrate the fluctuations in dielectric properties across different frequencies and temperatures. These findings offer valuable insights into the dielectric characteristics of beetroot.

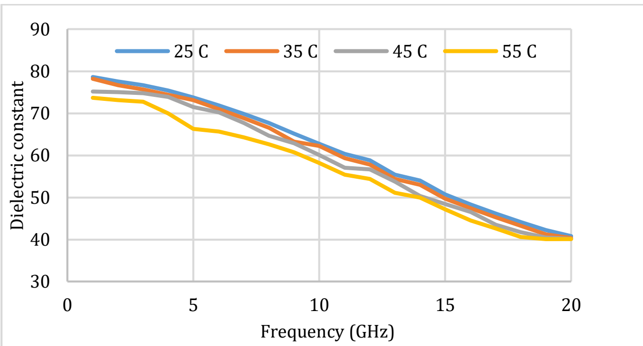

Fig. 3 Variation of the dielectric constant of beetroot with frequency at different temperatures

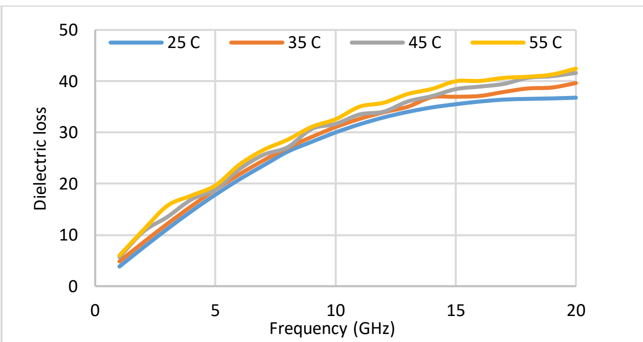

Fig. 4 Variation of the dielectric loss of beetroot with frequency at different temperatures

From the Fig. 3, it is visible that the dielectric constant of beetroot juice is decreasing with increase in frequency and temperature. It was observed that the dielectric constant (ε′) of beetroot juice decreased with an increase in frequency from 1 GHz to 20 GHz at 25 °C, the dielectric constant reduced from around 78 to 40. A similar decreasing trend was recorded at higher temperatures of 35 °C, 45 °C, and 55 °C, indicating that the dielectric constant diminishes consistently with increasing frequency across all temperature conditions. This decrease in dielectric constant may be because the water molecules and ions can't adjust quickly enough to the fast-changing electric fields at higher frequencies, so dielectric constant decreases due to dipole relaxation of water molecules and ionic polarization dynamics [7]. As the temperature rises, the increased movement of molecules makes it harder for them to stay aligned, which also reduces the dielectric constant. The dielectric constant of beetroot juice is primarily influenced by water content, with contributions from dissolved ions and carbohydrates [8].

The dielectric loss (ε′′) at various temperatures is shown graphically varying with frequency in Fig. 4. It was observed that the dielectric loss (ε″) of beetroot juice increased with rising frequency in the range of 1–20 GHz at 25 °C, the dielectric loss increased from approximately 4 at 1 GHz to about 43 at 20 GHz. A similar increasing trend was noted at higher temperatures of 35 °C, 45 °C, and 55 °C, indicating that both temperature and frequency significantly influence the energy dissipation behaviour of the sample. The increase in dielectric loss with frequency and temperature may be due to enhanced molecular motion, increased ion movement, and reduced dipole alignment with the alternating electric field, all of which led to greater energy dissipation in the form of heat.

The dielectric properties of food material vary with composition, moisture, frequency, and temperature. Water can be present in food materials in two possible ways; one is free and another in a bound state. When the moisture content in food materials rises, then dipoles also increase, as a consequence, this leads to an overall increase in the material's polarization [9]. So, these observations can be attributed to the polarization of its molecules and molecular stretching. Ionic conduction dominates the dielectric behaviour at lower frequencies, while dielectric relaxation losses dominate at higher frequencies [10]. These results provide new insights into the behaviour of dielectric properties as influenced by frequency and temperature, and they also provide baseline information for examining the dielectric properties of fruits and vegetables for exploring potential applications in quality monitoring.

4. Conclusion

The research assessed the dielectric properties of beetroot juice at different temperatures (25 °C, 35 °C, 45 °C, and 55 °C) and frequencies (ranging from 1 GHz to 20 GHz). A vector network analyser (VNA) was used in the study for measurement. The study elucidates the frequency- and temperature-dependent dielectric behaviour of beetroot juice, offering insights into its applications in microwave heating and food quality monitoring. The findings showed that the dielectric constant (ε′) decreases with increasing the frequency and temperature, and dielectric loss factor (ε″) increased with increased frequency and temperature. This trend suggests that higher temperatures promote dipolar relaxation and ionic mobility, leading to greater energy absorption and heating efficiency. Future studies could explore these findings in other food systems to optimize processing techniques.

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