



RESEARCH ARTICLE

Frequency and temperature-dependent dielectric behaviour of fresh Aloe vera at 1 to 20 GHz microwave frequency using time domain reflectometry

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Abstract

Aloe vera (AV), known for its gel-filled leaves, is potentially known for its therapeutic properties. It has created an interest in its applications in agriculture, medicine, cosmetics, materials science and sensors. Understanding the dielectric behaviour at different frequencies is crucial and significant to see the possibility of the use of potential biomaterials like AV for sensor development and for studying the electric response. The present study explores the dielectric behaviour of freshly cut AV leaf with its natural moisture within the microwave frequency range of 1 to 20 GHz using the time domain reflectometry (TDR) technique. The variation of complex dielectric constant, i.e., dielectric constant and dielectric loss of AV leaf as a function of frequency and temperature has been discussed in this paper. The Cole-Cole diagrams have also been presented. This is a unique effort to study the comprehensive analysis of the dielectric response of AV in the microwave region, which offers new insights into the electrical characteristics of AV.

Keywords

Dielectric constant; microwave; Aloe vera; TDR

Introduction

Aloe vera (AV) is a biochemical composition consisting of polysaccharides, amino acids, enzymes, vitamins, minerals, anthraquinones, phytosterols, and water as a major constituent (1, 2). The potentially active constituents of AV leaf collectively contribute to its multifaceted properties and applications (3, 4). The biophysical and biochemical studies of AV provide useful linkage to develop technological solutions for devising purposes. AV has been characterized by using scanning electron microscopy (SEM) and fourier transform infrared spectroscopy (FTIR), which provide the suitability of AV as nanofibers for applications in medical devices and would help to control the spreading of many diseases (5). The study of potential therapeutic properties of AV like hypoglycaemic, anticancer, gastro-protective, antifungal, and anti-inflammatory effects has been reported (6), which led to its applications in a variety of products, including foods, pharmaceuticals, and cosmetics (7). AV is a bio-organic herbal material widely used in the food, cosmetic, and pharmaceutical industries due to its availability and cost-effectiveness (8).

The dielectric properties of biomaterials at microwave frequency provide useful information for the assessment of quality parameters and molecular structure (9). It plays a crucial role in understanding the interaction between molecular constituents and electromagnetic fields of electromagnetic waves (10). This interaction is governed by dielectric parameters such as real dielectric constant and dielectric loss, which are significant in linking electromagnetic properties with the features of a material. The dielectric response of biomaterials like cancerous and normal tissues is significant for understanding biochemical and biophysical processes leading to sensor development (11). The dielectric mechanism for biomolecules like proteins, amino acids, cell membranes, and tissue-bound water is intended for clinical applications (12). The complex dielectric constant comprises the real part as the dielectric constant (ϵ'), which is a measure of a material's ability to store electrical energy and imaginary dielectric loss (ϵ''). Both ϵ' and ϵ'' are related by equation 1.

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (\text{Eqn.01})$$

Where $j^2 = -1$

Incident microwaves influence polar molecules and contribute to the dielectric mechanism of the material. AV leaf is primarily composed of water. The water content and the structure of polysaccharides in AV leaf can influence both the dielectric constant and loss as they are polar. This would change dielectric properties, influencing factors like polarization and relaxation processes in the material at high frequency electric fields. Because of this, there is a need to measure AV leaf's dielectric properties experimentally and discuss AV's dielectric behaviour changes.

After reviewing the related literature, very few attempts have been conducted at the dielectric characterization of AV gel material. Rarely a report is available for dielectric study of AV material in the microwave frequency range. The effect of microwave exposure on the AV and direct change in its resistive as the time of exposure increases have been studied using klystron microwave sources, a waveguide system, and an antenna at a single frequency (13). The electric response of bio-molecular films like proteins has been authenticated for potential applications of biomaterials as biosensors and dielectric coatings for electronic devices (14). It has been reported that instead of silicon oxide, the AV gel can be used as an effective dielectric material after electric characterization of SiO₂ and AV gel using two different models viz., Capacitive and dielectric barrier discharge models in COMSOL metaphysics. Hence, AV gel can be used as dielectric material in microelectronics devices (15).

There is a notable gap in the literature for dielectric measurements of AV in the microwave frequency range. No report is available for the dielectric response of AV due to changes in temperature and frequency in microwave regions. This motivates the conduct of microwave measurements for organic and biomaterials like AV for its

dielectric behaviour. This will explore the applicability of AV as a bio-dielectric material in the rapidly advancing field of microwave technology.

The present work consists of the dielectric behaviour of freshly cut AV plant leaves in the microwave frequency spectrum. This is the first attempt to conduct a frequency and temperature-dependent dielectric study of fresh AV leaf, especially at the microwave frequencies. The complex dielectric constant, i.e., dielectric constant, and dielectric loss (ϵ'') have been measured using a time domain reflectometer (TDR). These properties have been measured over a frequency range from 1GHz to 20GHz at different temperatures. The result provides valuable insights into the electrical characteristics of AV, laying the groundwork for potential applications in various scientific and technological domains.

Materials and Methods

Fresh AV leaf has been obtained directly from the plant located near the laboratory. The leaf was cut and covered in an airtight polyethylene bag to avoid alteration in its physical properties and then immediately transported to the laboratory. The natural moisture of the sample of AV leaf was 98.17%, measured by the gravimetric method on the weight basis using the following equation 2.

The leaf was then cut across its cross-section so that the gel material of the leaf should be exposed, as shown in Fig. 1. It makes it possible for the probe connected to TDR to be

$$\% \text{ Gravimetric moisture} = \frac{(W_s - W_d) \times 100}{W_s} \quad (\text{Eqn. 2})$$

immersed into AV leaf gel.



Fig. 1a & b. Sample of Aloe vera leaf cut across cross-section to expose gel material.

Where, W_s - Weight of sample; W_d -Weight of dry sample

TDR has proven to be a valuable tool for characterizing the dielectric properties of materials in the time domain (16, 17). This technique allows for precise measurements of the propagation characteristics of electromagnetic waves through the material under investigation. The application of TDR in the context of AV dielectric studies provides a dynamic and real-time analysis of its response to varying frequencies. The complex

dielectric spectra for AV leaf have been measured at 10°C and 23°C in the frequency range of $1 \leq \nu/\text{GHz} \leq 20$. We have used a Tektronix digital serial analyzer DSA 8300 sampling mainframe oscillator with dual channel sampling module 80E10B. The sampling module provides a 12ps incident and 15ps reflected rise time pulse produced by the tunnel diode. This pulse travelled through a coaxial cable having a 50-ohm impedance. The inner and outer diameters of the coaxial cable were 0.28mm and 1.19mm, respectively. The sampling oscilloscope records the changes in step pulse reflection from the end of the line. The reflected pulse without sample $R_1(t)$ and with sample $R_x(t)$ were recorded in the time window of 5 ns and digitized at 2000 points. The subtraction [$q(t)=R_1(t)-R_x(t)$] and addition [$p(t)=R_1(t)+R_x(t)$] of these pulses were done and stored in oscilloscope memory. Fourier transformation has been used for the conversion of time domain data to frequency domain data in the frequency range $1 \leq \nu/\text{GHz} \leq 20$. Calibration of TDR was done according to the guidelines of manufacturers and using solvents with known dielectric constant (18).

$$\epsilon^*(\nu) = \epsilon_\infty + \frac{(\epsilon_s - \epsilon_\infty)}{[1 + (i2\pi\nu\tau)^{1-\alpha}]^\beta} \quad \text{Eqn.3}$$

The block diagram and experimental set-up of the TDR and temperature control unit are as shown in Fig.2 & 3. The complex dielectric spectra for AV have been obtained by using Havriliak-Negami equation 3.

Where,

ϵ_∞ - permittivity at the high frequency limit;

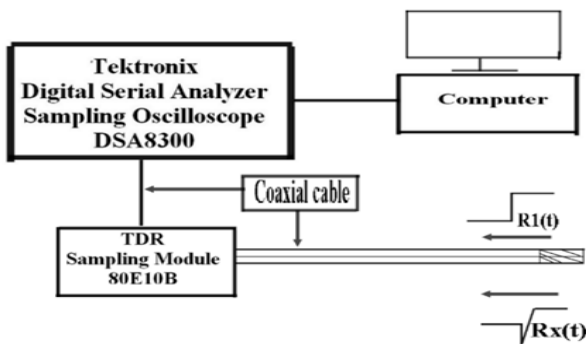


Fig.2. Block diagram of an experimental set of time domain reflectometer.



Fig.3. Experimental set of time domain reflectometer and temperature controlling unit

ϵ_s -the static, low frequency permittivity;

τ -the characteristic relaxation time of the medium;

α and β - describe the asymmetry and broadness of the corresponding spectra;

ν - Frequency

$i^2 = -1$

Results and Discussion

An oscillating electric field causes molecular mobility in the AV leaf. This molecular mobility is governed by the dielectric characteristics; at microwave frequency, it provides significant information about the molecular structure of the material (19). The dielectric characteristics in turn are dictated by the water and cellular constituents of AV.

In Fig. 4, the ϵ' for distilled water and AV leaf both at 23 °C shows a decreasing trend with increasing frequency. This is the theoretical agreement with the concept of dielectric polarization of dipoles at the microwave frequencies (20). AV leaf contains 97.27% of water. This ϵ' contributes to the rotation of the water molecule at microwave frequency. For lower frequencies, the orientation of the water molecule is well aligned with the frequency of the microwave, but as frequency increases, the orientation of the water molecule lags behind the microwave frequency and the molecule is unable to relax; hence, polarizability is decreased with an increase in the frequency of the microwave. The ϵ' of water was higher compared with the AV leaf at 23 °C for frequencies from 1 GHz to 20 GHz. The difference in ϵ' between the distilled water and AV leaf is due to the role of ionic conductivity in leaf material. The average difference in the magnitude of their dielectric constant ϵ' was around 12 up to 15 GHz. While above 15 GHz to 20 GHz, the average difference in the magnitude of their ϵ' was 7. This might be due to the ease of rotation of water molecules bound to the bulk part of the AV leaf as frequency increases. The plot of ϵ' for AV gel, recorded for 10 °C and 23 °C, shows an intersection at 5.9 GHz. Higher values of the ϵ' were observed before the frequency of 5.9 GHz, i.e., 1 GHz to 5.9 GHz for 10 °C compared to ϵ' values at 23 °C, and the trend was reversed after 5.9 GHz, i.e., for 10 °C, lower ϵ' values compared to ϵ' values at 23 °C were observed with increasing frequency.

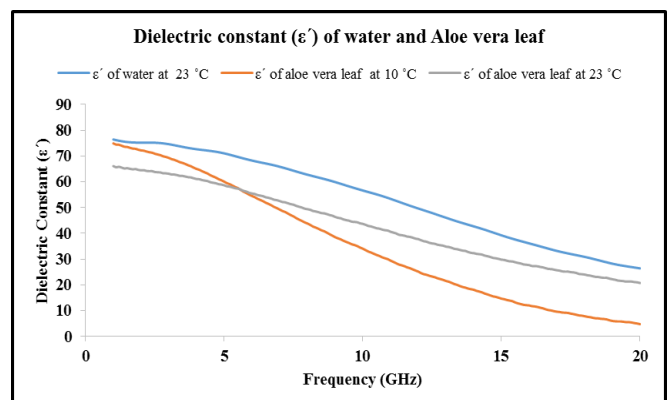


Fig.4. Dielectric constant (ϵ') of water and Aloe vera plant leaf at 23 °C and 10 °C

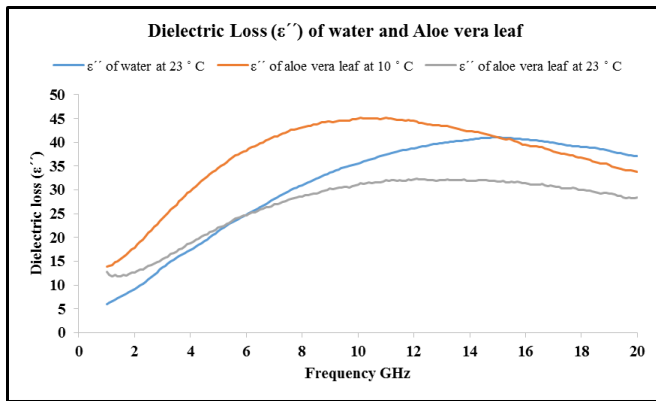


Fig.5 Dielectric loss ϵ'' of water at 23 °C and Aloe vera at 10 °C and 23 °C

Fig. 2 shows that the dielectric constant ϵ' of AV at both 10 °C and 23 °C decreases with increasing frequency from 1 GHz to 20 GHz.

Fig.5 shows the dielectric loss ϵ'' of water at 23 °C and AV at temperatures of 10 °C and 23 °C. The ϵ'' starts to increase from 1.0 GHz and then ϵ'' increases with frequency, attaining a maximum value at a frequency of 10 GHz for 10 °C and 12 GHz for 23 °C. Above these frequencies, ϵ'' decreases with an increase in frequency for both the temperatures. The ϵ'' for water increases with increasing frequencies from 1 GHz to 14.9 GHz; it shows a maximum loss value at 14.9 GHz, and further up to 20 GHz decrease in ϵ'' was observed.

Comparing the dielectric loss ϵ'' of water and AV at 23 °C, it was observed that loss for AV and water almost overlapped from 4.8 GHz to 6.8 GHz. At frequencies 1 GHz to 4.7 GHz, the loss factor for AV gel was higher than water; however, the trend reverses above 6.9 GHz, where the loss of water goes on increasing with frequency compared with AV. At lower frequencies, the dielectric loss in plant tissue might be dominated by processes such as ionic conduction and dipole rotation. As the frequency increases, these processes may become less significant, leading to a decrease in dielectric loss. Water tends to exhibit higher dielectric loss at lower frequencies, and this effect may contribute to the observed differences.

The Cole-Cole plot is also plotted and presented, as it is significant in vegetation studies for its ability to provide information about the electrical properties of plant tissues (Fig. 6). This information is valuable for assessing plant health, understanding growth dynamics, and optimizing agricultural practices in a non-destructive and non-invasive manner (21).

Conclusion

AV leaf electrical properties, especially its dielectric response to microwave frequency, are essential to comprehending both the plant's molecular makeup and physiological dynamics. Molecular mobility in the leaf is induced by the oscillating electric field and is principally controlled by the amount of water and cellular components. Because Aloe vera leaves contain most of the water, the dielectric behaviour of the plant reflects the rotational dynamics of water molecules at microwave frequencies. The

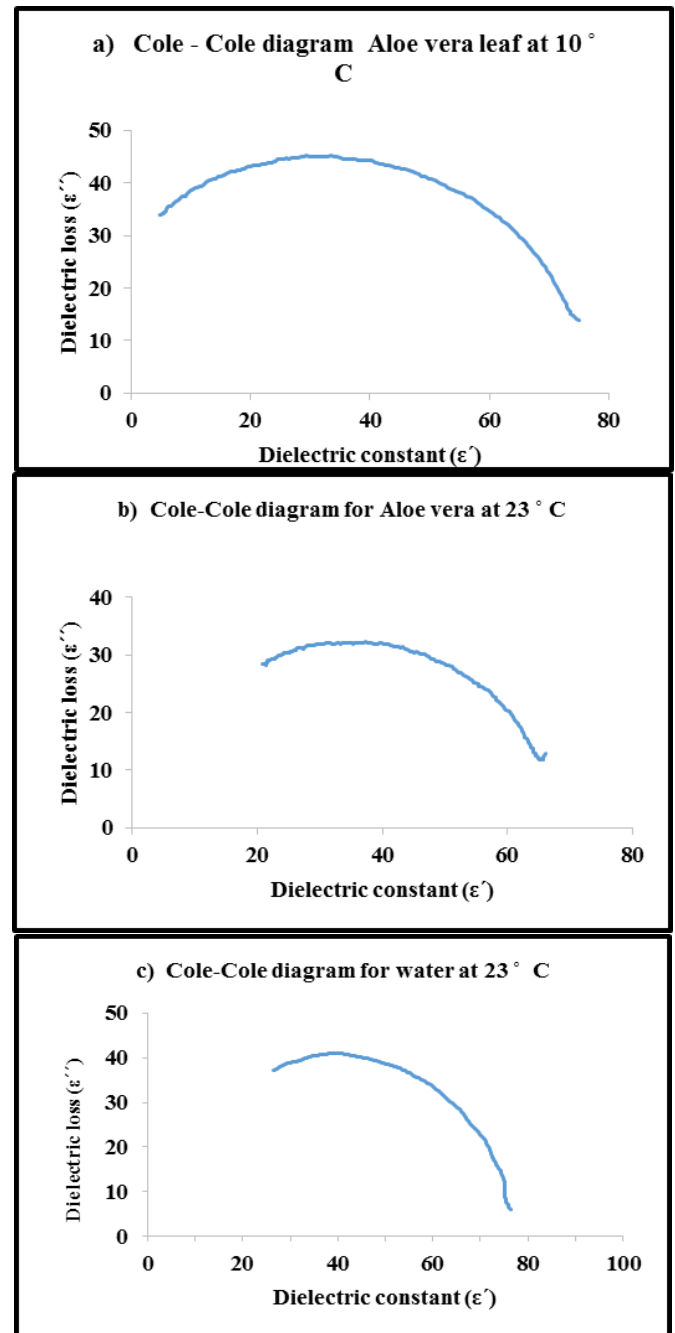


Fig.6. Cole-Cole Plot for a) Aloe vera leaf at 10 °C, b) Aloe vera at 23 °C c) water at 23 °C

dielectric constant (ϵ') of water was higher compared with the AV leaf at 23 °C for frequencies from 1 GHz to 20 GHz, which is theoretically in agreement. The ϵ' of AV at both 10 °C and 23 °C decreases with increasing frequency from 1 GHz to 20 GHz, which is supported by the polarisation mechanism of dipoles with a change in frequency of incident radiations. The ϵ' of Aloe vera leaf was compared at 10 °C and 23 °C, showing variations in dielectric behaviour (at greater than 15 GHz) indicating that ionic conductivity may have an impact on the latter frequencies. The dielectric loss (ϵ'') of water at 23 °C and AV at temperatures of 10 °C and 23 °C displayed similar trends: starting from 1.0 GHz, ϵ'' increases with frequency, reaching peak values at 10 GHz for 10 °C and 12 GHz for 23 °C. Beyond these frequencies, ϵ'' declines with increasing frequency for both temperatures. Additionally, the graphs of the Cole-Cole plot will serve as a valuable tool in vegetation studies, offering insights into the

electrical properties of plant tissues for assessing plant health and optimizing agricultural practices in a non-destructive manner.

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Authors' contributions

AI coordinated this study for the literature survey, research design, sample selection, measurements, calculations, data preparation, and data analysis and has participated in the writing of this manuscript. AJ is involved in the preparation of data, data analysis and interpretation. AD carried out measurements of the sample using time domain reflectometry (TDR) and calculation of dielectric constant and loss from raw data. AK provided access to the experimental setup and mentored the overall research.

Compliance with ethical standards

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

Ethical issues: None.

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