Research Article

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Investigation of Dielectric Properties of Potato, Tomato and Onion Juices at Microwave Frequencies

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ABSTRACT

The dielectric properties of fresh juices of *Solanum tuberosum* (potato), *Solanum lycopersicum* (tomato) and *Allium cepa* (onion) were measured in terms of the dielectric constant and dielectric loss factor, over a frequency range from 1 to 50 GHz and at temperatures ranging from 30 to 60 °C, by using the PNA network analyzer model E8364C and open-ended coaxial probe 85070E. A prediction of relaxation frequencies of molecules for the three different juices was done and their molecular behavior was then studied by plotting dielectric constant *vs.* frequency and dielectric loss factor *vs.* frequency curves in the frequency range from 1 to 50 GHz at four different temperatures from 30 to 60 °C. The dielectric properties of food products play a crucial role in determining their heating behavior when subjected to an electromagnetic field. Understanding these properties is essential for the development of microwave pasteurization and sterilization processes tailored to various food products.

Keywords: Dielectric constant; Dielectric loss factor; Relaxation frequency; Temperature; Potato; Tomato; Onion.

1. INTRODUCTION

The investigation of dielectric properties in materials holds significant importance as they serve as a measure of how electromagnetic energy interacts with substances at microwave and radio frequencies. Nelson (2005) extensively discusses and defines these properties. The interest in the dielectric properties of agricultural products stems from their application in microwave and radio frequency dielectric heating, where they play a crucial role in transforming microwave energy into heat (Muthukumarappan and Swamy, 2019). The dielectric properties are represented by a complex quantity (ε*), known as the permittivity of the material, which comprises two components: the dielectric constant (ε′) indicating the ability to store electrical energy, and the dielectric loss (ε″) representing the ability to convert electrical energy into heat. These two properties are related through Equation (1), as given by

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \qquad (1)$$

where $j = \sqrt{-1}$. The ratio of the abstract part to the real part of complex permittivity (ε*) is called the loss tangent (tan δ), given by

$$\tan\delta = \frac{k''}{k'} = \frac{\varepsilon''}{\varepsilon'} \qquad (2)$$

where, k′ is the relative dielectric constant and k″ is the relative dielectric loss; $k' = \varepsilon' / \varepsilon_o$ and $k'' = \varepsilon'' / \varepsilon_o$ where, ε_o is the free space permittivity (ε_o= 8.854 x 10^{-12} F/m).

The dielectric properties of foods are influenced by several factors, including frequency, temperature, moisture content and food composition (Resurreccion Jr *et al*. 2015). When the frequencies exceed 1 GHz, dipole polarization becomes significant, whereas frequencies below 1 GHz are dominated by ionic losses (Ryynänen, 1995). The interaction between substances and electromagnetic fields leads to various types of dielectric losses such as polar, electronic, atomic and Maxwell-Wagner losses (Regier and Schubert, 2005) (Equation 1).

In food materials containing organic matter, water and salt, an increase in salt content generally results in higher dielectric losses at a specific frequency. This is due to the fact that ions, water and salt act as conductors in the presence of an electromagnetic field (İçier and Baysal, 2004). High-moisture foods exhibit a dielectric constant that decreases as the frequency increases. This phenomenon occurs because higher frequencies cause a faster alternation of the electromagnetic field, making it more challenging for water molecules and clusters to rapidly orient or change polarization with the field. Elevated temperatures increase the Brownian motion of water molecules, which reduces energy storage (Franco *et al.* 2015). Substituting water with less polarizable substances, such as oil, also leads to lower values of ε' (Sosa-Morales *et al*. 2010).

Studies conducted by Feng *et al*. (2002), Guan *et al*. (2004), Ikediala *et al*. (2000), and Wang *et al*. (2003) examined the impact of temperature and frequency on the dielectric properties of various fruits and vegetables. Calay *et al.* (1995) found that the dielectric constant of fruits tends to increase with temperature. The behavior of the loss factor, however, depends on the operating frequency. At higher frequencies, the loss factor generally increases with rising temperature, as observed by Nelson (2003) and Sosa-Morales *et al.* (2009).

The dielectric properties of various fruit juices, including apple, pear, orange, grape and pineapple, were investigated by Zhu *et al.* (2012), within a frequency range of 20 to 4,500 MHz and temperatures ranging from 15 to 95 °C. Their findings revealed a consistent decrease in ε' (dielectric constant) with increasing frequency, while ε' exhibited an almost linear increase with rising temperature.

In another study, Nelson and Bartley (2002 a) measured the dielectric properties of a commercial apple juice product across the frequency range of 200 MHz to 20 GHz. They observed that the presence of liquid water, which has a relaxation frequency of 19.2 GHz at 25°C, significantly influenced the dielectric properties of apple juice. Furthermore, as the temperature increased, the relaxation frequency shifted to higher frequencies.

Nelson and Bartley (2002 b) employed an open-ended probe and water jacket, along with additional temperature control equipment, to investigate the temperature and frequency dependence of dielectric properties in liquid, semisolid and pulverized food materials. Their study covered a broad frequency range and provided insights into the influence of various water forms, such as free water, bound water, rotationally hindered water and dielectric relaxation mechanisms, on the dielectric properties.

Ahmed *et al.* (2009) conducted a study to measure the dielectric properties of potato flour-water dispersions (slurry) in the frequency range of 500–2500 MHz. They utilized the open-ended coaxial probe method with a network analyzer to investigate the variations in dielectric properties concerning concentration (10–25% w/w) and temperature (20–75 °C). Both commercially available and laboratory-prepared potato flour samples were examined. The results revealed that the dielectric constant (ε') decreased with increasing temperature and frequency, but it increased with higher concentration. On the other hand, the loss factor (ε'') increased with frequency and concentration, while its relationship with temperature showed mixed effects.

Singh (2018) measured the dielectric constant and dielectric loss of tomato sauce at various moisture levels, achieved by adding salt. The measurements were performed within the radio frequency range of 100 kHz to 1 MHz and at temperatures ranging from 25 to 50 °C. The results revealed significant changes in the dielectric properties with the variation of the moisture levels and salt content.

Lurwan *et al.* (2021) studied the dielectric properties of two different tomato varieties, namely Roma and Cherry. They used an LCR meter to measure the dielectric constant and dielectric loss at frequencies of 50, 90 and 120 kHz. The measurements were carried out at three distinct temperatures: 35, 45 and 55°C. The experimental findings revealed that for all the samples, both the dielectric constant and dielectric loss factor decreased with increasing frequency. Additionally, as the temperature increased, the dielectric constant decreased while the dielectric loss factor increased for all the samples.

Several literature sources have reported successful applications of microwave (MW) technology in liquid foods such as fruit juices (Franco *et al.* 2017; Mendes-Oliveira *et al.* 2020; Siguemoto *et al.* 2019), milk (Zhu *et al.* 2014; Pina-Pérez *et al.* 2014), purees (Benlloch-Tinoco, 2014; Brinley, 2007), sauces (Kim *et al.* 2018), sugarcane juice (Alvi *et al.* 2019), massecuite (Bento *et al.* 2006) and creams (Giuliani *et al.* 2010). While the use of radio frequency (RF) heating in liquid foods is less common, it has been applied in milk (Awuah *et al.* 2005), kiwi puree (Lyu *et al.* 2018), fish soup (Muñoz *et al.* 2022) and liquid egg (Zhu *et al.* 2021).

In industrial applications, the accurate measurement of dielectric properties holds great significance. An understanding of these properties is crucial in designing heating applicators, determining optimal frequency ranges, developing new products, and selecting appropriate package sizes and materials (Zhu *et al.* 2012).

However, there is a lack of reliable dielectric data on the dielectric properties of potato, tomato and onion at frequencies above 20 GHz in the existing literature. Most studies that have been reported on the dielectric properties of fruits and vegetable juices have focused on frequencies below 20 GHz. It has been reported by Hasted (1973) that the relaxation frequencies of water molecules extend beyond 20 GHz, especially at temperatures above 30 °C; since water is the major component in these juices, it is reasonable to expect valuable insights into the dielectric behavior of juices at frequencies above 20 GHz and temperatures above 30 °C. Therefore, in this research, the dielectric constant and loss factor of the juices of potato, tomato and onion have been measured in the frequency range of 1 to 50 GHz and temperatures of 30 °C and above, to investigate their dielectric behavior at these frequencies and temperatures.

2. MATERIALS AND METHOD

Fresh samples of potatoes, tomatoes and onions of Indian varieties were purchased from a local fruit market, CEERI, Pilani, India and were washed with running tap water and dried with paper towels. Potatoes were peeled off and the upper layers of onions were removed. The samples of all three vegetables were cut into pieces by using a stainless-steel knife and juices were extracted using a slow juice extractor SSJ 4043WH, Sensor (seeds of tomato were removed automatically during juice extraction). A PNA network analyzer (Model: Agilent E8364C, Agilent Technology) with an open-ended coaxial probe (85070E, Hewlett Packard) was used to measure the dielectric properties of potato, tomato and onion juices. The juice samples were placed in a wide glass beaker (200 ml) and the open co-axial probe (probe diameter ≈2.4 mm) was set into the beaker. The samples were heated from 30 to 60 °C and were maintained at temperatures 30, 40, 50 and 60 °C by using a constant temperature bath, while dielectric properties were measured in the frequency range of 1 to 50 GHz, at each such temperature. The detailed procedure of the dielectric measurement is reported elsewhere (Vijay *et al.* 2015).

3. RESULTS AND DISCUSSION

3.1 POTATO JUICE

In Fig. 1, the variation of ε' with frequency is shown for temperatures 30 to 60 °C, over the frequency range 1 to 50 GHz for fresh juice of potato. It is observed that at all temperatures, ε' decreases continuously with increasing frequency, the rate of decrease being higher at lower temperatures. It is also observed that the ε'-f curves at 30 and 40 °C, intersect each other at a frequency of about 6 GHz, while the curves at 50 and 60 °C, intersect each other at a frequency of about 14 GHz. Thus, the curves for different temperatures intersect each other somewhere in the frequency region (6 GHz ≤ f ≤ 14 GHz). These curves show dielectric dispersion with respect to this intersection frequency region. This region almost overlaps the range of relaxation frequencies which has been reported to be from 7.3 GHz to 17.6 GHz by Kuang and Nelson (1997), at 23 °C. Below this frequency region (f < 6 GHz), ε' decreases with increasing temperature, whereas above this frequency region (f > 14 GHz) ε' increases with increasing temperature. The range of frequencies (6 GHz ≤ f ≤ 14 GHz) obtained for potato from the present research is also in agreement with the results of Nelson et al., (1994), according to which, the relaxation frequency of fresh fruits lies well above the frequency of water (2.45 GHz) but lower than the relaxation frequency of water, which is 17.11 GHz at 20 °C. At 30 °C, the ε'-f curve is almost smooth but small amplitude vibrations are obtained in ε'-f curves at higher temperatures (40-60 °C) at frequencies (35-50 GHz). Potato juice contains dissolved carbohydrates as active ingredients. According to Kudra *et al*. 1992, the presence of carbohydrates is related to the stabilization of hydrogen bonding patterns through hydroxyl–water interaction which reduces the effect of water activity. Hence, small vibrational peaks are obtained for potato juice at higher temperatures (40-60 °C) and higher frequencies (35–50 GHz).

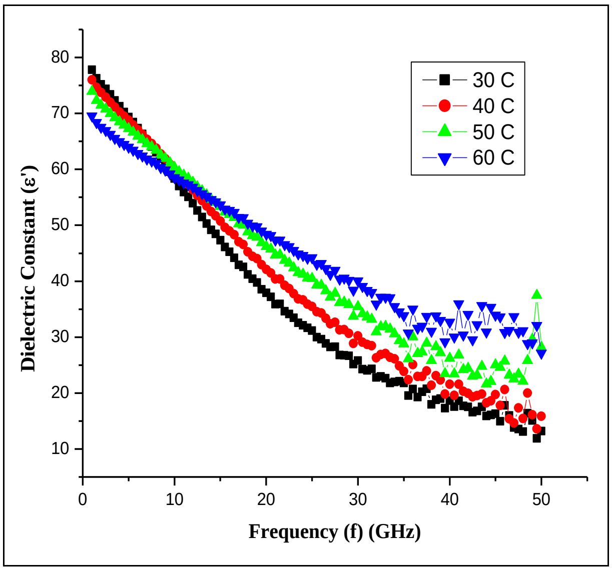

Fig. 1: Frequency dependence of the dielectric constant (ε') of potato juice at indicated temperatures

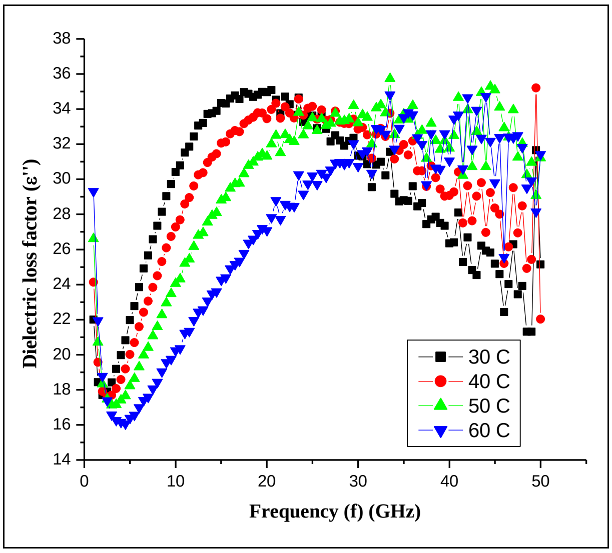

Fig. 2: Frequency dependence of the dielectric loss factor (ε'') of potato juice at indicated temperatures

In Fig. 2, we display ε''-f curves for potato juice at different temperatures. At 30 °C, the ε''-f curve starts from about 1 GHz and then shows a minima at about 2.5 GHz, beyond which, ε'' increases with frequency. It acquires a peak value at about 19 GHz, which may be due to the relaxation frequency. Kuang and Nelson (1997) reported the value of relaxation frequency for potato juice at 23 °C which is 17.6 GHz. This study shows that the relaxation frequency of potato juice is 18 GHz at the temperature of 30 °C, which lies in the vicinity of the frequency corresponding to the maxima of ε" – f curve. Beyond this frequency, the value of ε" slowly decreases but ε" shows strong oscillations in between 30 to 50 GHz. Even at 40 °C, the behavior of ε"-f curve is similar to that of 30 °C, but the maxima positions shift to higher frequencies. At higher temperatures (50-60 °C), the curves acquire a saturation state around 30 GHz and thereafter strong oscillations in the form of vibrational peaks are obtained. In the low-frequency region, minima are obtained at all temperatures between 1 to 2.5 GHz, the position of minima shifting to higher frequencies side as the temperature increases, as reported by Mudgett *et al*. 1980. Below minima frequencies, ε" increases with an increase in temperature, whereas at frequencies above the minima frequency, ε" decreases with an increase in temperature. In the low-frequency region, a very high value (= 29.32) of ε" is obtained at about 1 GHz for the temperature of 60 °C. This feature may be attributed to the presence of complex starch in the potato juice. The large amplitude vibrations obtained at all the temperatures at frequencies above 30 GHz may also be attributed to the presence of starch in the potato juice.

3.2 TOMATO JUICE

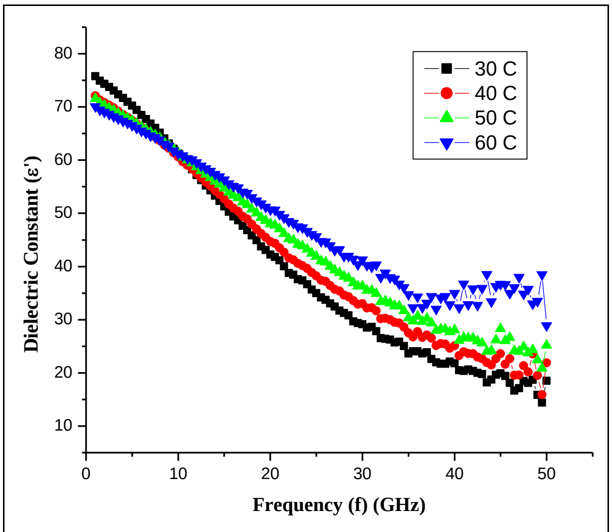

Fig. 3: Frequency dependence of the dielectric constant (ε') of tomato juice at indicated temperatures

In Fig. 3, the variation of ε' with frequency is shown for temperatures 30 to 60 °C, over the frequency range 1 to 50 GHz, for fresh juice of tomato. The general behavior of ε'-f curves for tomato juice is similar to that of potato juice. Like potato juice, ε' decreases continuously with increasing frequency, at all temperatures, in this case as well. However, now the ε'-f curves at all temperatures intersect each other very close to the frequency of 10 GHz. These curves show dielectric dispersion below and above this frequency region around 10 GHz. Below this region of dielectric dispersion, ε' decreases with increasing temperature and above this region of dielectric dispersion, ε' increases with increasing temperature, which may be due to the effect of relaxation frequency. In this case, at temperatures from 30 to 50 °C, only small vibrational peaks are obtained above 40 GHz, whereas at 60 °C the vibrational peaks become prominent and somewhat similar to those of water, which suggests that though water plays an important role in the dielectric properties of tomato juice, sufficient amount of dissolved salt molecules are also present in tomato juice, lowering activity of water at lower temperatures (30 to 50 °C). The vibrational peaks observed at higher temperatures (50-60 °C) in the frequency region (40-50 GHz), may be considered to arise due to the molecular liberation in tomato juice.

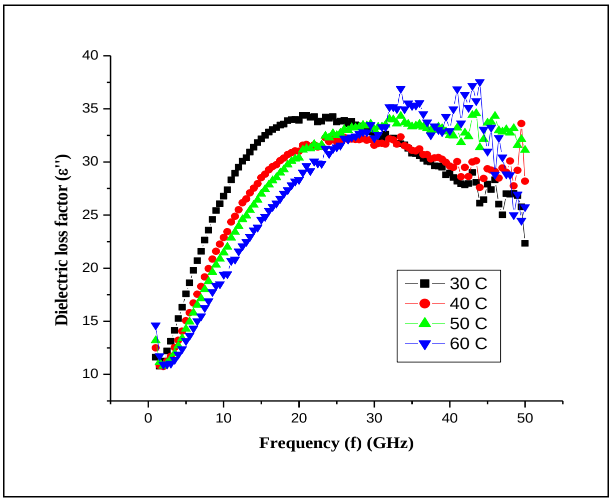

Fig. 4: Frequency dependence of the dielectric loss factor (ε") of tomato juice at indicated temperatures

Fig. 4 depicts the ε"-f curves for tomato juice at different temperatures. At low temperatures (30 °C), the ε"-f curve starts from a minima at about 1.0 GHz and then ε" increases with frequency, attaining a maximum value at a frequency of about 20 GHz, which may be considered to arise due to the relaxation frequency, as explained in case of potato. Above this frequency, ε" decreases with frequency and rapid oscillations are obtained in the frequency range above 40 GHz. At 40 °C as well, we obtain a similar curve but now the ε"-f curve after starting from 1 GHz, shows a clear minima at about 2.0 GHz in the low-frequency region and the maxima position shifts to the higher frequencies side. At higher temperatures (50-60 °C), we obtain rapid oscillations in the curves at frequencies above 29 GHz, where the curves at different temperatures cross each other, which may be considered to arise as a result of molecular liberation in the presence of salts. In the lower frequency range (1- 2.5 GHz), ε"-f curves show a minima. At frequencies below the minima ε" increases with increasing temperature, whereas for frequencies above the minima frequency, a reverse trend is observed - ε" decreases with an increase in temperature. The above-mentioned features observed for tomato juice in the frequency range of 1-2.5 GHz are characteristic of all those juices that have salty nature, which is in accordance with the findings reported by Mudgett *et al*. (1980).

3.3 ONION JUICE

In Fig. 5, the variation of ε' with frequency is shown for four temperatures (30, 40, 50 and 60 °C) over the frequency range 1 to 50 GHz for fresh juice of onion. It is observed that at all four temperatures, ε' decreases continuously with increasing frequency. It is also observed that the ε'-f curves for 30 and 40 °C intersect each other at a frequency of about 6 GHz, while the curves at 40, 50 and 60 °C intersect each other at a frequency of about 9.5 GHz. Thus, the ε'-f curves for different temperatures intersect each other somewhere in the frequency region of 6 GHz ≤ f ≤ 9.5 GHz. These curves show dielectric dispersion with respect to this intersect frequency region. Below the region of dielectric dispersion, ε' decreases with increasing temperature and above this region, ε' increases with increasing temperature, which may be due to the effect of relaxation frequency. The general behavior of the ε'-f curves for onion juice is similar to that of tomato shown in Fig. 3. Small amplitude vibrational peaks are now obtained at higher temperatures (50 and 60 °C) and at frequencies above 44 GHz, which suggests that there is sufficient amount of dissolved salt molecules in onion juice. A small peak observed at a temperature of 60 °C and a small dip at 50 °C at a frequency of about 48 GHz, may be considered to arise due to the molecular liberations in the presence of salts.

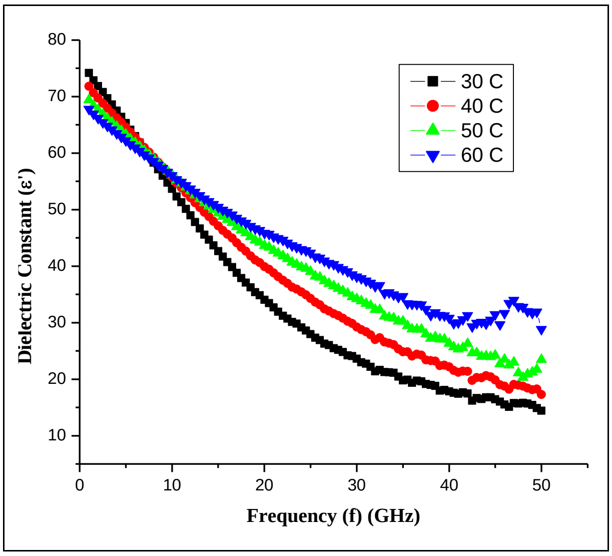

Fig. 5: Frequency dependence of the dielectric constant (ε') of onion juice at indicated temperatures

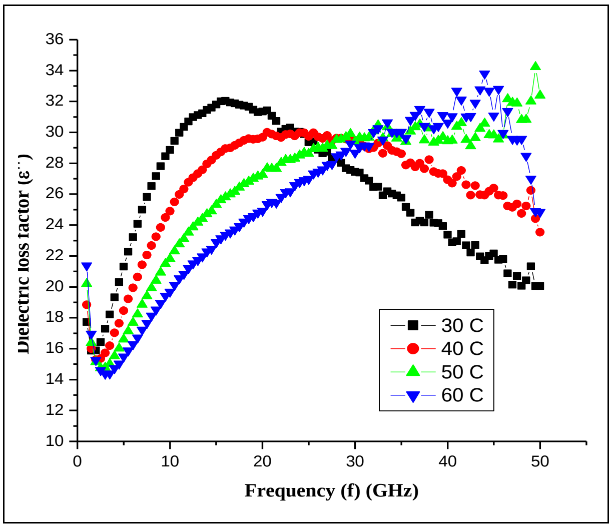

Fig. 6: Frequency dependence of the dielectric loss factor (ε'') of onion juice at indicated temperatures

In Fig. 6, we display ε''-f curves for onion juice at four different temperatures (30, 40, 50 and 60 °C). The general behavior of these curves is similar to that of tomato juice. At 30 °C, ε'' first decreases with frequency showing a minima at about 2.0 GHz; then ε'' increases with frequency and the ε''-f curve acquires a maximum value at about 15.5 GHz, which may arise due to its relaxation frequency. Kuang and Nelson (1997) reported the value of relaxation frequency for white onion to be 15.2 GHz at 23 °C. This study shows that the relaxation frequency of white onion juice at 30 °C is 16 GHz, which is close to the frequency of maxima in the ε''-f curve. At frequencies greater than 15.5 GHz, ε'' is found to decrease steadily, except for small variations between 45 and 50 GHz. In the lower frequency range (1- 2.5 GHz), ε''-f curves show a minima and below the minima frequency ε'' increases with increasing temperature; whereas above the minima, opposite behavior of ε'' is observed - ε'' decreases with increasing temperature. This feature is observed for the juices which have salty nature and this is in accordance with the findings reported by Mudgett *et al*. 1980 in the frequency range of 1-5 GHz. At 40 °C as well, a graph similar to that at 30 °C is obtained, but with the difference that now the maxima of ε''-f curve is obtained at about 22 GHz and above this frequency, ε'' decreases more slowly as compared to that at 30 °C. At 50 °C, the ε''-f curve acquires almost a uniform average value at frequencies above 30 GHz, along with a rising peak in the vicinity of 50 GHz; whereas at 60 °C, the ε''-f curve rises steadily up to 40 GHz and thereafter shows a peak at about 45 GHz and then falls rapidly. The appearance of vibrational peaks at higher temperatures and in higher frequency ranges may be considered to arise due to water playing a major role at these temperatures and frequencies.

CONCLUSION

The presence of starch in potato juice and salt in the juices of tomato and onion govern the behavior of their dielectric dispersion. The ε'-f curves at different temperatures show opposite behavior on two sides of the region of intersection, which almost matches the relaxation frequencies of water present in these juices. Similarly, in the ε''-f curves, opposite behavior on two sides of minima is observed on increasing the temperature. Further, the vibrational peaks at higher temperatures (50 and 60 °C) in the higher frequency region were also obtained for all three juices under investigation, due to molecular liberation in the presence of starch and salts and excitation of water molecules at these frequencies.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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