CHAPTER – 4

Frequency and temperature dependence of dielectric properties of juices of fruits and vegetables

4.1 Introduction

The fundamental parameters which describe the interaction of electromagnetic radiation with matter are the dielectric properties and therefore dielectric data of materials is helpful in effectively deciding and developing applications of materials based on their electrical properties. The dielectric properties of materials provide information about the capacitive properties related to energy storage and energy losses in materials as a result of their interaction with electromagnetic fields (Barbosa-Canovas et al., 2006).

The knowledge of complex permittivity of different types of substances at microwave frequencies is of special interest in different areas of research, such as, molecular behaviour in liquids and solids, behaviour of different types of soils, processing of food materials, radiation absorbers, electrical behaviour of different types of foods and biological samples, microwave circuit design etc. The dielectric properties of materials are also important for industrial applications because they provide information about the electrical and magnetic characteristics and molecular behaviour of the materials, which prove to be quite useful in research and development of a number of industries, viz., ferrite devices, microwave oven, microwave circuits, food processing, moisture meters etc.

The study of the dielectric properties of fruits and vegetables and their frequency dependence provides us necessary guidelines for selecting optimum frequencies of electromagnetic radiation and finding out appropriate values of electric field so as to achieve optimum heating rates, and to determine the maximum thickness of the treated dielectric slab permittivity for the uniform RF and microwave treatments to take place. Such information is of great importance in optimizing and automation of processes in food industry. Nelson and Dutta (2001)
reported that in high moisture foods, the dielectric properties are influenced not only by the water content but also by dissolved constituents and ionic conduction. Mudgett (1985) reported that the organic constituents of majority of foods have \((\varepsilon' < 3\) and \(\varepsilon'' < 0.1\)) hence they may be considered as dielectrically inert as compared to aqueous ionic fluids or water having higher values of dielectric constant. Because of the low values of \(\varepsilon'\) and \(\varepsilon''\), the energy absorption by such materials is also low and they may be considered to be almost transparent to energy. At very low moisture levels, when the remaining traces of water are in bound state and remain unaffected by the rapidly changing radio or microwave (MW) fields, the components of specific heat are the only factors that decide dielectric heating.

Most of the studies reported on dielectric properties of juices of fruits and vegetables are at frequencies lower than 20 GHz. However, the relaxation frequencies of molecules in water have been reported to lie at frequencies beyond 20 GHz at temperature above 30\(^\circ\)C. Since water is the major component of juices, useful information regarding behaviour of dielectric constant \((\varepsilon')\) and dielectric loss factor \((\varepsilon'')\) in juices may be expected at frequencies higher than 20 GHz at temperatures above 30\(^\circ\)C. As such, in the present research dielectric constant and loss factor of juices were measured in the frequency range 1 to 50 GHz by using coaxial probe system (85070E) with PNA Network Analyzer (E8364C).

In this chapter the experimental values of permittivity of 10 fruits and 4 vegetables in the frequencies \((1-50\ \text{GHz})\) and temperatures \(30^\circ\text{C to } 60^\circ\text{C}\), as obtained by using coaxial probe and Network Analyzer method, are reported in graphical form. The relevant data is included in the thesis in tabular form in Appendix A (Tables: A 1 to A 15).

The permittivity data (dielectric constant and loss factor) for the two cultivars of apple, (Red delicious and Fuji), two cultivars of grapes, (Sultania and Black monukka), two cultivars of watermelon (Sugar baby and Arka manik), pomegranate, orange, sweet lime, cucumber, potato, tomato, lemon and onion as obtained from the present work, at temperatures \(30^\circ\text{C to } 60^\circ\text{C}\) and frequencies from
1 GHz to 50 GHz are given in Tables A 2 to A 15 (Appendix). In order to observe molecular behavior in these samples, we plot graphs showing variation of dielectric constant (\(\varepsilon'\)) and loss factor (\(\varepsilon''\)) with frequency at different temperatures. Such plots for \(\varepsilon'\) and \(\varepsilon''\) of different samples are given in Figures 4.5 to 4.35.

4.2 Sample preparation and calibration of Network Analyzer

For experimental study, the samples are taken in the form of juice. The juice of the fruits and vegetables is extracted by using a L. G. made juicer and filtered by using a fine grain filter paper. The dielectric constant (\(\varepsilon'\)) and loss factor (\(\varepsilon''\)) of the fresh juice of fruits and vegetables were measured in the frequency range 1 GHz to 50 GHz by using a PNA network analyzer, model Agilent E8364C. The test probe consists of an open ended coaxial probe system (Agilent, 85070E). The system software calculates the dielectric properties of the sample from changes in the phase and amplitude of the microwave signal delivered by the probe of open-ended coaxial line due to reflection at the interface with the sample to be analyzed. The calibration of the Network analyzer is done by using three different loads, viz., (i) air, (ii) a short circuit with the metal contacts, and (iii) distilled water at room temperature. The calibration curve for water is given in Fig. 4.1, showing variation of \(\varepsilon'\) and \(\varepsilon''\) with frequency (in the frequency range 1-50 GHz) at room temperature (250°C). After calibration, the analyzer and the probe system are tested by taking measurements on a standard liquid (methanol, in the present case) of known dielectric properties. The measured values of dielectric constant (\(\varepsilon'\)) and loss factor (\(\varepsilon''\)) for methanol at frequencies 1 to 50 GHz at room temperature (250°C) are displayed in Fig. 4.2, along with standard dielectric data (up to 5 GHz) reported by National Physical Laboratory, Delhi (Gregory and Clarke, 2012) and the values reported by Misra et al. (1990) up to 20 GHz. The values of dielectric parameters for methanol above 20 GHz are not available in literature for a meaningful comparison.
The agreement of the measured values of $\varepsilon'$ and $\varepsilon''$ with the standard data and the values reported by Misra et al. (1990) confirms the accuracy of measurements. The temperature control of the sample is done by using a Haake B3 Constant Temperature Circulator with a digital control module, in which cold / hot water is
circulated through the jacket surrounding the sample cup. The digital temperature controller provides temperature stability of the sample within \( \pm 0.1 \, ^{\circ}\text{C} \).

### 4.3 Permittivity values of water

In this chapter the experimental permittivity values of fresh juice of fruits and vegetables are reported. Water is the dominant factor of all the hygroscopic materials, such as agri-foods, and particularly in the fruits and vegetables. The dielectric properties of materials depend on their chemical composition and in particular on the permanent dipole moments associated with their molecules or with the molecules of water and any other substance making up the material of interest. Dielectric polarization under the influence of external electric field and lagging of the polarization vector behind the high frequency electric field by virtue of the inertia of the molecules, are the phenomenon responsible for the frequency dependence of dielectric properties (Venkatesh and Raghavan, 2004). The temperature dependence of the dielectric properties of materials is a complex phenomenon. It may increase or decrease with the temperature depending on the nature of material.

In its pure form, water is a classic example of a polar dielectric. The water molecules behave as dipoles with dipole moment \( 6.2 \times 10^{-30} \text{Coulomb-meter} \). Water is the major absorber of microwave energy in the foods and consequently, the higher the moisture content, the better the heating. Microwave heating of foods is therefore greatly affected by the presence of water in them (Mudgett, 1985; Nelson and Kraszewski, 1990). The amount of free water in a substance also plays a major role in deciding its dielectric constant, since the dielectric constant of free water is high (~78 at room temperature \( 25 \, ^{\circ}\text{C} \)) and frequency 2.45 GHz. It is now well known that in juices of fruits and vegetables water is present in Free State, therefore the dielectric properties of the juices of fruits and vegetables are very much influenced by the dielectric properties of water. In Figs. 4.3 and 4.4, variation of dielectric constant \( (\varepsilon') \) and loss factor \( (\varepsilon'') \) respectively of water with frequency is shown for temperatures \((30^{\circ}\text{C to 60}^{\circ}\text{C})\) over the frequency range 1 GHz to 50 GHz. From Fig. 4.3, it is observed that as the frequency is increased from 1 GHz to 50 GHz, \( \varepsilon' \) decreases with frequency at all temperatures, the rate of decrease with frequency being faster at low temperatures and slow at higher temperatures. It is also observed that the \( \varepsilon'\)-f curves for at 30\(^{\circ}\text{C} \) and 40\(^{\circ}\text{C} \), intersect each other at frequency 8.5 GHz,
while the curves at 50\(^0\) and 60\(^0\)C, intersect each other at frequency 14.5 GHz. Thus, the \(\varepsilon'\)-\(f\) curves for different temperatures intersect each other somewhere in the frequency region \((8.5 \text{ GHz} \leq f \leq 14.5 \text{ GHz})\). These curves show dielectric dispersion to this intersection frequency region. Below this frequency region \((f < 8.5 \text{ GHz})\) \(\varepsilon'\) decreases with increasing temperature whereas above this frequency region \((f > 14.5 \text{ GHz})\) \(\varepsilon'\) increases with increasing temperature. This behavior of variation of \(\varepsilon'\) with frequency at different temperatures may be attributed to the effect of temperature on the dispersion of EM waves in water. Further, it can be noticed from Fig. 4.3 that at low temperature \((30^0\text{C})\), a smooth curve of \(\varepsilon'\)-\(f\) is obtained, but at higher temperatures \((40-60^0\text{C})\) and at higher frequencies \((35-50 \text{ GHz})\) overlapping of many absorption peaks are observed. When temperature is increased, both the strength and extent of the hydrogen bonding decrease. These results in lowering of dielectric constant at low frequencies but at high frequencies oscillations of dipoles are faster and since at high temperatures molecular agitations also increase. At high temperatures, increased molecular agitations and rapid oscillations under the influence of high frequency EM radiation result in fluctuations in \(\varepsilon'\) values, giving rise to zig-zag behavior, i.e., ups and downs in \(\varepsilon'\)-\(f\) curves at high temperatures in the high frequency region \((35–50 \text{ GHz})\).

![Graph showing frequency dependence of dielectric constant (\(\varepsilon'\)) of water at indicated temperatures](image)

**Fig. 4.3** Frequency dependence of the dielectric constant (\(\varepsilon'\)) of water at indicated temperatures
This is because in liquid water the molecular stretching and molecular librations shift the frequency of molecular vibrations to higher side, on raising the temperature (as hydrogen bonding weakens at higher temperatures, the covalent O-H bonds strengthen causing them to vibrate at higher frequencies) (Praprotnik et al., 2004).

![Graph showing frequency dependence of dielectric loss factor (\(\varepsilon''\)) of water at indicated temperatures]

**Fig. 4.4 Frequency dependence of the dielectric loss factor (\(\varepsilon''\)) of water at indicated temperatures**

From Fig. 4.4, it is observed that at low temperature (30°C) dielectric loss factor (\(\varepsilon''\)) of water increases with increasing frequency, acquires a maximum value at a frequency of about 19.5 GHz (relaxation frequency) and then slowly decreases with increasing frequency. A smooth \(\varepsilon''\)-f curve is obtained at this temperature (30°C). An increase in temperature, reduces the drag associated with the rotation of the water molecules, so reducing the friction and hence the dielectric loss. As such, in the low frequency region the value of \(\varepsilon''\) at a particular frequency decreases as the temperature is increased, as observed from Fig. 4.4. As the temperature increases, the relaxation time decreases (i.e., relaxation frequency increases) and hence the loss factor maxima shifts to higher frequencies, as evidenced by Fig. 4.4, from which it is apparent that the maxima in \(\varepsilon''\)-f curves shifts from 19.5 GHz to about 38.0 GHz as the temperature is increased from 30°C to 60°C. In the higher frequency range (30
– 50 GHz) where the operating frequency is greater than the relaxation frequency, re-orientation process of water molecules is becomes active. The re-orientation process may be modeled by using a ‘wait-and-switch’ process where the water molecules have to wait for a period of time until favorable orientation of neighboring molecules occurs and then the hydrogen bonds switch to the new molecule (Kaatze et al., 2002)). At these frequencies (30 to 50 GHz) and at higher temperatures (40 to 60°C), multiple relaxation losses are observed.

The microwave dielectric properties of liquid water as obtained from the present work at 50°C temperature are compared for certain microwave frequencies with the values reported by Hasted (1973) in Table 4.1, given below.

**Table 4.1 Microwave dielectric properties of water at indicated frequencies and at 50°C temperature along with other results due to Hasted (1973)**

<table>
<thead>
<tr>
<th>Present Study</th>
<th>Results adapted from Hasted (1973)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>ε'</td>
</tr>
<tr>
<td>1.5</td>
<td>70.96</td>
</tr>
<tr>
<td>3.0</td>
<td>70.46</td>
</tr>
<tr>
<td>4.5</td>
<td>69.74</td>
</tr>
<tr>
<td>7.5</td>
<td>67.50</td>
</tr>
<tr>
<td>9.0</td>
<td>65.92</td>
</tr>
<tr>
<td>12.5</td>
<td>62.22</td>
</tr>
<tr>
<td>17.5</td>
<td>56.54</td>
</tr>
<tr>
<td>26.5</td>
<td>46.23</td>
</tr>
<tr>
<td>36.5</td>
<td>37.74</td>
</tr>
</tbody>
</table>

From Table 4.1 it is observed that the present results at all the frequencies are in good agreement with the values reported by Hasted (1973) at nearly the same frequency except that the present value of loss factor at frequency 26.5 GHz, shows
some erratic behavior and also does not match with the value reported by Hasted. The present value of $\varepsilon''$ at 1.5 GHz is also somewhat lower than the value reported by Hasted, which may be accounted for by the 13.3% difference in frequency used by Hasted as compared to the present case.

4.4 Present Results for Permittivity values of fruits and vegetables juices

4.4.1 Permittivity of Red delicious apple juice

In Fig. 4.5, the variation of $\varepsilon'$ with frequency is shown for temperatures (30°C to 60°C) over the frequency range 1 GHz to 50 GHz for fresh juice of red delicious apple. It is observed that $\varepsilon'$ decreases with increasing frequency at all the temperatures. It is also observed that the $\varepsilon'$-f curves for at 30°C and 40°C, intersect each other at frequency 6.5 GHz, while the curves at 50°C and 60°C, intersect each other at frequency 14.0 GHz. Thus, the $\varepsilon'$-f curves for different temperatures intersect each other somewhere in the frequency region (6.5 GHz ≤ f ≤ 14.0 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 10.2 GHz to 16.4 GHz by Kuang and Nelson (1997) at 23°C. Below this frequency region (f < 6.5 GHz) $\varepsilon'$ decreases with increasing temperature whereas above this frequency region (f > 14.0 GHz) $\varepsilon'$ increases with increasing temperature. The range of frequencies (6.5 GHz ≤ f ≤ 14.0 GHz) obtained for red delicious apple 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 i.e., 2.45 GHz but lower than the relaxation frequency of water, which is 17.11 GHz at 20°C. On comparing these curves with those of water (Fig. 4.3) it is apparent that now we do not obtain vibrational peaks as obtained for water at higher temperatures in the frequency range 35-50 GHz. This may be accounted for by the presence of dissolved ingredients in the juice of red delicious apple. In the case of high carbohydrate foods and syrups, the dissolved sugars (in water) are the main microwave (MW) susceptors (Mudgett, 1986).
In Fig. 4.6, the variation of ε'' with frequency has been shown at different temperatures, (30° - 60°C) for red delicious apple. It is observed that at low temperatures (30°C to 50°C) ε'' increases with increasing frequency, reaches a maximum value and then show decreasing behaviour with increasing frequency. However, at 60°C, the dielectric loss factor (ε'') slowly increases with frequency and above 30 GHz it acquires almost a uniform value about which fluctuations in ε'' are obtained as are observed in water at high temperatures in the frequency range (35-50 GHz). This suggests that at high temperatures water in juice plays an important role as far as losses are concerned. At 30°C, peak value of loss factor is observed at about 16 GHz which is found to shift to about 23 GHz at 40°C and to about 28 GHz at 50°C. Funebo and Ohlsson (1998) reported that at a point the relaxation frequency and the operating frequency are close to each other, this is where the peak value of the relative loss factor should occur.
Fig. 4.6 Frequency dependence of the dielectric loss factor ($\varepsilon''$) of red delicious apple at indicated temperatures

This is exactly the behavior of the loss factor seen in the results of this work at 30°C. Further, the shift in frequency corresponding to the peak value of loss factor as the temperature is increased may be considered due to the decrease in relaxation time, except at 60°C for which no distinguished peak is obtained in $\varepsilon''$-$f$ curve. At higher temperatures (50-60°C) and at higher frequencies (40 to 50 GHz) relaxation losses are observed in $\varepsilon''$-$f$ curves due to molecular stretching and molecular librations.

The present value of $\varepsilon'$ for red delicious apple at 2 GHz and temperature 30°C is 70.85, which is in good agreement with the value 70.4 reported by Wang et al. (2003) for red delicious apple (pulp) at a frequency of 1.8 GHz and temperature 20°C. The present value of loss factor for red apple juice $\varepsilon''$ is 11.18 at 2 GHz frequency and temperature of 30°C, which agrees well with the value 10.8 reported by Wang et al. (2003) for delicious apple (pulp) at 1.8 GHz and temperature 20°C.

4.4.2 Permittivity of Fuji apple juice

In Fig. 4.7, the variation of $\varepsilon'$ with frequency is shown for temperatures (30°C to 60°C) over the frequency range 1 GHz to 50 GHz for fresh juice of fuji
apple. $\varepsilon'$-f curves of fuji apple show almost similar behavior as shown by $\varepsilon'$-f curves for red delicious apple. $\varepsilon'$ continuously decreases with increasing frequency at all temperatures. $\varepsilon'$-f curves at 30$^0$C and 40$^0$C, intersect each other at frequency 5.0 GHz, while the curves at 50$^0$C and 60$^0$C, intersect each other at frequency 19.5 GHz. Thus, the $\varepsilon'$-f curves for different temperatures intersect each other somewhere in the frequency region ($5.0 \text{ GHz} \leq f \leq 19.5 \text{ GHz}$). 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 10.1 GHz to 15.8 GHz by Kuang and Nelson (1997) at 23$^0$C. Below this frequency region ($f < 5.0 \text{ GHz}$) $\varepsilon'$ decreases with increasing temperature whereas above this frequency region ($f > 19.5 \text{ GHz}$) $\varepsilon'$ increases with increasing temperature.

![Dielectric Constant vs Frequency graph]

**Fig. 4.7 Frequency dependence of the dielectric constant ($\varepsilon'$) of fuji apple juice at indicated temperatures**

Comparatively large difference between $\varepsilon'$ values for fuji apple juice at 50$^0$C and 60$^0$C in the frequency range 1 to 5 GHz may be noticed from its $\varepsilon'$-f curves. This difference may be attributed to the amount of pectins in the juice of fuji apple in which structure changes take place at about 60$^0$C. At higher frequencies (above say 43 GHz) and at higher temperatures (50-60$^0$C), very small vibrational peaks are
observed due to the fact that dissolved sugar and salt present in the apple juice suppress the dielectric constant.

In Fig. 4.8, the variation of \( \varepsilon'' \) with frequency is shown for temperatures (30°C to 60°C) over the frequency range 1 GHz to 50 GHz for fresh juice of fuji apple. It is found that \( \varepsilon'' \) first increases with increasing frequency, acquires a maximum value at temperatures (30-40°C) and then decreases with increasing frequency. The maxima in \( \varepsilon'' \)-\( f \) curve at 30°C temperature is observed at about 16 GHz at temperature 30°C, which is less than the relaxation frequency of water. The position of maxima in \( \varepsilon'' \)-\( f \) curve shifts to about 19 GHz at 40°C. At higher frequencies (i.e., above 30 GHz) the \( \varepsilon'' \)-\( f \) curves at 30°C and 40°C merge with each other and show small fluctuations in the value of \( \varepsilon'' \) at frequencies greater than 45 GHz. The \( \varepsilon'' \)-\( f \) curves at 50°C and 60°C do not show a maxima, and become almost flat at frequencies above 28 GHz. At these temperatures enlarged relaxation losses are also observed at frequencies greater than 37 GHz, which may arise due to molecular stretching and molecular liberations.

The values of \( \varepsilon' \) and \( \varepsilon'' \) at frequencies 1 and 10 GHz and at temperature 50°C, as reported by Nelson and Bartley (2002) for commercial apple juice, are
reproduced below in Table 4.2 along with the relevant data from present studies for juice of two varieties of Indian apple, for the sake of comparison.

Table 4.2 Dielectric properties of apple juice at two frequencies (at temperature 50°C)

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Sample</th>
<th>1 GHz</th>
<th>10 GHz</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ε'</td>
<td>ε''</td>
<td>ε'</td>
</tr>
<tr>
<td>1.</td>
<td>Red Delicious apple</td>
<td>64.58</td>
<td>5.85</td>
<td>54.42</td>
</tr>
<tr>
<td>2.</td>
<td>Fuji apple</td>
<td>66.53</td>
<td>6.584</td>
<td>56.77</td>
</tr>
</tbody>
</table>

It is observed that the present values of ε' as well as ε'' for the two varieties are slightly lower than the values of these parameters for commercial apple juice reported by Nelson and Bartley at both the frequencies. This difference in behavior of fresh juice of two varieties of apple with that of commercial apple juice may be attributed to the difference in granular structure and molecular arrangement in different varieties of apple, moreover, the commercial apple juice may have preservatives added to it for its safe storage.

In Table 4.3 the values of ε' and ε'' for the juice of red delicious apple obtained from the present study at different temperatures and frequency 2.0 GHz are compared with the relevant values reported by Wang et al. (2003) for red delicious apple in solid form at 1.8 GHz. It may be observed that at a particular frequency, the values of ε' and ε'' for apple juice decrease with increasing temperature. The Present results for ε' and ε'' of red delicious apple juice at 2.0 GHz at different temperatures are in good agreement with the reported values of these parameters by (Wang et al., 2003) at 1.8 GHz and relevant temperatures, small differences between the two sets of data may be accounted for due to slight difference between the frequencies used and in the physical states (solid or liquid) of samples used in the two cases.
Table 4.3 Dielectric parameters for Red delicious apple juice at different temperatures and at indicated frequencies

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Frequency (GHz)</th>
<th>30°C</th>
<th>40°C</th>
<th>50°C</th>
<th>60°C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ε'</td>
<td>ε''</td>
<td>ε'</td>
<td>ε''</td>
<td>ε'</td>
</tr>
<tr>
<td>1.</td>
<td>2.0</td>
<td>70.85</td>
<td>11.18</td>
<td>68.3</td>
<td>9.29</td>
<td>63.4</td>
</tr>
<tr>
<td>2.</td>
<td>1.8</td>
<td>68.3</td>
<td>9.4</td>
<td>66.1</td>
<td>8.3</td>
<td>64.0</td>
</tr>
</tbody>
</table>

4.4.3 Permittivity of Green grapes juice (Sultania)

![Graph](image.png)

**Fig. 4.9** Frequency dependence of the dielectric constant (ε') of green grapes juice at indicated temperatures.

In Fig. 4.9, the variation of ε' with frequency is shown for temperatures (30°C to 60°C) over the frequency range 1 GHz to 50 GHz for fresh juice of green grapes. It is observed that ε' decreases continuously with increasing frequency at all temperatures, except for 60°C. At 60°C the value of ε' decreases with frequency up to 15 GHz and thereafter it remains almost uniform up to 19 GHz and thereafter it shows fluctuations in the form of vibrational peaks and a decrease in its average...
value is noticed beyond 30 GHz. It is also observed that at 30°C and 40°C, \( \varepsilon' \)-f curves intersect each other at frequency 5 GHz, while as at 50°C and 60°C, these curves intersect at frequency 10 GHz. Thus, the \( \varepsilon' \)-f curves for different temperatures intersect each other somewhere in the frequency region \( (5 \text{ GHz} \leq f \leq 10 \text{ GHz}) \). These curves show dielectric dispersion with respect to this intersection frequency region. Below this frequency region \( (f < 5 \text{ GHz}) \) \( \varepsilon' \) decreases with increasing temperature whereas above this frequency region \( (f > 10 \text{ GHz}) \) \( \varepsilon' \) increases with increasing temperature due to the effect of relaxation frequency. The high temperature behavior of \( \varepsilon' \) at higher frequencies may be attributed to the fact that in grape juice carbohydrate (dissolved sugars) are the main MW susceptors (Mudgett, 1986), which reduce the water activity at higher temperatures and higher frequencies, since in materials containing sugars, the free water is influenced by the hydroxyl groups of the sugars, and hydrogen bonds are stabilized, as observed by Tulasidas et al. (1995) for grapes.

![Graph of Frequency Dependence of Dielectric Loss Factor](image)

**Fig. 4.10 Frequency dependence of the dielectric loss factor (\( \varepsilon'' \)) of green grapes juice at indicated temperatures**

In Fig. 4.10, the variation of \( \varepsilon'' \) with frequency is shown for temperatures (30°C to 60°C) over the frequency range 1 GHz to 50 GHz for fresh juice of green grapes (Sultania). It is observed that at low temperatures (30 and 40°C), \( \varepsilon'' \) of green...
grapes increases with increasing frequency, reaches its maximum value (at about 10 GHz for 30\(^0\)C and 12 GHz at 40\(^0\)C) and then decreases with increasing frequency and show vibrational peaks between 45 and 50 GHz. At higher temperatures (50 and 60\(^0\)C), \(\varepsilon''\) shows a different behavior, i.e., it increases with increasing frequency till it acquires a maximum value (at about 12 GHz), then shows a shallow dip at about 16 GHz for both the temperatures. Thereafter \(\varepsilon''\) increases and acquires almost a uniform average value at 50\(^0\)C and continuously increasing trend at 60\(^0\)C. The \(\varepsilon''\)-f curves for all the temperatures cross each other at 22 GHz and there after \(\varepsilon''\) at 50\(^0\)C shows small amplitude vibrational peaks up to 50\(^0\)C. At 60\(^0\)C, large amplitude vibrational peaks are obtained between 22 GHz and 50 GHz. The peak value obtained in \(\varepsilon''\)-f curves for 30\(^0\)C temperature at about 10 GHz shifts to about 12 GHz at higher temperatures (40 – 60\(^0\)C) due to decrease in relaxation time at higher temperatures. In the lower frequency range (1 – 2.5 GHz) a different feature is observed i.e., \(\varepsilon''\) of green grape juice increases with increasing temperature may be due to the acidic nature of green grape juice. It may be possible that in this region the ionic component of juice increases with increasing temperature and dominant the dipole loss. This results in to an increase in dielectric loss with increase in temperature (Mudgett et al., 1980). At higher temperatures (50-60\(^0\)C) and at higher frequencies (30-50 GHz) relaxation losses peaks are observed in the \(\varepsilon''\)-f curves which may arise due to molecular stretching and molecular liberations.

4.4.4 Permittivity of Black grapes juice (Black Monukka)

In Fig. 4.11, the variation of \(\varepsilon'\) for black grapes (Black Monukka) with frequency has been shown at different temperatures (30\(^0\)C - 60\(^0\)C). The general behavior of the curves for black grapes is similar to that of green grapes. At higher temperatures and higher frequencies also similar behavior as observed in green grapes is also observed in black grapes, however for black grapes the \(\varepsilon'\)-f curves are more smooth and systematically vary with frequency as compared to green grapes at all temperatures.
Fig. 4.11 Frequency dependence of the dielectric constant ($\varepsilon'$) of black grapes juice at indicated temperatures

At 30°C and 40°C, $\varepsilon'$-f curves intersect to each other at frequency 5.5 GHz, while as at 50°C and 60°C, these curves intersect at frequency 9.5 GHz. Thus, the $\varepsilon'$-f curves for different temperatures intersect each other somewhere in the frequency region (5.5 GHz ≤ $f$ ≤ 9.5 GHz). These curves show dielectric dispersion with respect to this intersection frequency region. Below this frequency region ($f < 5.5$ GHz) $\varepsilon'$ decreases with increasing temperature whereas above this frequency region ($f > 9.5$ GHz) $\varepsilon'$ increases with increases temperature may be due to the effect of relaxation frequency. In comparison of green grape juice, the thermal dispersion region shifts slightly towards the lower frequency side may be due to the difference in molecular structure of both the juices.

In Fig. 4.12, the variation of $\varepsilon''$ for black grapes (Black Monukka) with frequency has been shown at different temperatures (30°C - 70°C). It is observed that $\varepsilon''$ increases with frequency at all temperatures up to 25 GHz, where the $\varepsilon''$-f curves at all the temperatures cross each other. It is observed that at 30°C and 40°C $\varepsilon''$ increases with frequency and acquires a maximum value (at about 18 GHz for 30°C and at about 22 GHz for 40°C), there after $\varepsilon''$ decreases with increase in
frequency and in the higher frequency all temperatures up to 25 GHz, where the $\varepsilon''$-$f$ curves at all the temperatures cross each other. Below 25 GHz as we increase the temperature, $\varepsilon''$ is observed to decrease.

![Graph](image)

**Fig. 4.12 Frequency dependence of the dielectric loss factor ($\varepsilon''$) of black grapes juice at indicated temperatures**

Above 25 GHz a reverse trend is observed i.e., $\varepsilon''$ increases with increasing temperature. Above frequencies 40 GHz, vibrational peaks are also observed. At higher temperatures (50°C and 60°C), $\varepsilon''$ after acquiring a maximum value at about 25 GHz has almost uniform average value at 50°C and further increase at 60°C. Vibrational peaks of higher magnitudes are also observed at 50°C and 60°C at frequencies above 30 GHz. At higher temperatures (50°C - 60°C) and higher frequencies, vibrational peaks are observed due to relaxation losses.

In the low frequency region (1 – 2.5 GHz), there is no found any increment in $\varepsilon''$ of black grape juice with increasing temperature. This shows that black grape juice is not acidic.

The present values of $\varepsilon'$ and $\varepsilon''$ for green grapes and black grapes at 2.5 GHz and temperatures 30°C to 60°C are displayed in Table 4.4 along with the values of $\varepsilon'$
and $\varepsilon''$ at frequency 2.45 GHz for the pulp of seedless Thomson grapes reported by Tulasidas et al. (1995) at the corresponding temperatures, for the sake of comparison.

**Table 4.4 Dielectric parameters of grapes at different temperatures**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Sample</th>
<th>30°C</th>
<th>40°C</th>
<th>50°C</th>
<th>60°C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\varepsilon'$</td>
<td>$\varepsilon''$</td>
<td>$\varepsilon'$</td>
<td>$\varepsilon''$</td>
<td>$\varepsilon'$</td>
</tr>
<tr>
<td>1</td>
<td>Green grapes (Sultania)</td>
<td>67.93</td>
<td>15.55</td>
<td>66.42</td>
<td>13.89</td>
<td>63.84</td>
</tr>
<tr>
<td>2</td>
<td>Black grapes (Black monukka)</td>
<td>63.98</td>
<td>5.87</td>
<td>67.61</td>
<td>8.21</td>
<td>65.79</td>
</tr>
<tr>
<td>3</td>
<td>Thompson Seedless grape</td>
<td>68</td>
<td>17</td>
<td>66</td>
<td>15</td>
<td>63</td>
</tr>
</tbody>
</table>

It may be observed from the table that the present values of $\varepsilon'$ for the two cultivars at all the temperatures are in good agreement with the values reported by Tulasidas et al. (1995). However, the present values of loss factor ($\varepsilon''$) for black grapes at all the temperatures are observed to be lower than the $\varepsilon''$ values of green grapes and the values reported by Tulasidas et al. (1995) for Thompson seedless grapes.

**4.4.5 Permittivity of Green Watermelon (Sugar baby) juice:**

In Fig. 4.13, the variation of $\varepsilon'$ for green watermelon (Sugar baby) with frequency has been shown at different temperatures (30°C - 60°C). It is observed that $\varepsilon'$ continuously decreases with increasing frequency at all temperatures. It is also observed that the $\varepsilon'$-f curves for at 30°C and 40°C, intersect to each other at frequency about 5.5 GHz, while the curves at 40°C, 50°C and 60°C, intersect each other at frequency about 12.5 GHz. Thus, the curves for different temperatures intersect each other somewhere in the frequency region (5.5 GHz ≤ f ≤ 12.5 GHz). These curves show dielectric dispersion with respect to this intersection frequency region. Below this frequency region (f < 5.5 GHz) $\varepsilon'$ decreases with increasing
temperature whereas above this frequency region \((f > 12.5 \text{ GHz})\) \(\varepsilon'\) increases with increasing temperature may be due to the effect of relaxation frequency. Watermelon juice has sweet nature due to soluble solids content (Nelson et al. 2006). At lower temperature 30\(^{0}\)C, a smooth \(\varepsilon'\)-f curve is observed i.e., no prominent vibrational peaks are observed even in the higher frequency range, but at higher temperatures (40-60\(^{0}\)C) we obtain prominent vibrational peaks in the frequency range 35- 50 GHz. As temperature increases the vibrational peaks become more and more strong.

![Graph showing dielectric constant vs frequency at different temperatures](image)

**Fig. 4.13 Frequency dependence of the dielectric constant \((\varepsilon')\) of green watermelon juice at indicated temperatures**

On comparing Fig. 4.13 with Fig. 4.4 for water it may be concluded that water plays an important role in deciding dielectric properties of watermelon, particularly the vibrational peaks obtained at higher temperatures in the higher frequency region.

In Fig. 4.14, the variation of \(\varepsilon''\) for green watermelon (Sugar baby) with frequency has been shown at different temperatures (30\(^{0}\)C - 60\(^{0}\)C). It is observed that at the lowest temperature (30\(^{0}\)C), \(\varepsilon''\) increases with increasing frequency, reaches its maximum value at about 16 GHz then decreases with increasing
frequency. As discussed earlier, the maximum value of $\varepsilon''$ observed at about 16 GHz in this case may correspond to the relaxation frequency.

![Dielectric loss factor vs Frequency](image)

**Fig. 4.14 Frequency dependence of the dielectric loss factor ($\varepsilon''$) of green watermelon juice at indicated temperatures**

Relaxation frequency increases with increasing temperature, therefore the frequency corresponding to maximum value of $\varepsilon''$ shifts towards the higher frequency side, reaching 20 GHz for 40°C. At higher temperatures (50-60°C) $\varepsilon''$ is observed to acquire almost uniform average value at 50°C and increase with increasing frequency at 60°C. Many relaxation loss peaks are observed in higher frequency range (30 – 50 GHz) at higher temperatures (40-60°C), which are more prominent for 60°C. This behavior of green watermelon may on comparison with Fig. 4.4, be again attributed to the major contribution from water.

**4.4.6 Permittivity of Striped watermelon (Arka manik) juice:**

In Fig. 4.15, the variation of $\varepsilon'$ for striped watermelon (Arka manik) with frequency has been shown at different temperatures (30°C - 60°C). The general trends of $\varepsilon'$-$f$ curves for striped watermelon are similar to the green watermelon. As for the general behavior of $\varepsilon'$ – $f$ curves, $\varepsilon'$ is observed to decrease continuously with increasing frequency.
Dielectric Constant ($\varepsilon'$)

**Fig. 4.15 Frequency dependence of the dielectric constant ($\varepsilon'$) of striped watermelon juice at indicated temperatures**

It is observed that the $\varepsilon'$-f curves for at $30^0$ and $40^0$C, intersect to each other at frequency about 7.5 GHz, while the curves at $40^0$, $50^0$ and $60^0$C, intersect each other at frequency about 11.5 GHz. Thus, the curves intersect each other somewhere in the frequency region ($7.5 \text{ GHz} \leq f \leq 11.5 \text{ GHz}$). These curves show dielectric dispersion with respect to this intersection frequency region. Below this frequency region ($f < 7.5 \text{ GHz}$) $\varepsilon'$ decreases with increasing temperature whereas above this frequency region ($f > 11.5 \text{ GHz}$) $\varepsilon'$ increases with increasing may be due to the effect of relaxation frequency.

At lowest temperature ($30^0$C), $\varepsilon'$-f curve is almost smooth, but at higher temperature ($40 - 60^0$C) vibrational peaks are observed in the frequency range 35 to 50 GHz due to molecular stretching and molecular librations in watermelon juice. It is observed that the dielectric behaviour of two cultivars of watermelon is nearly same.

In Fig. 4.16, the variation of $\varepsilon''$ for striped watermelon (Arka manik) with frequency has been shown at different temperatures ($30^0$C - $60^0$C). The general
behaviour of $\varepsilon''$-$f$ curves for striped watermelon are observed to be similar to those of green watermelon.

![Graph showing frequency dependence of dielectric loss factor (ε'') of striped watermelon juice at indicated temperatures](image)

**Fig. 4.16 Frequency dependence of the dielectric loss factor (ε'') of striped watermelon juice at indicated temperatures**

As the frequency is increased $\varepsilon''$ at 30°C increases with frequency and acquires a maximum value at about 17 GHz, thereafter it decreases with frequency. Almost smooth curve is obtained at this temperature. At 40°C also a similar variation of $\varepsilon''$ with frequency is obtained, the frequency of maxima shifting to about 21 GHz and thereafter average value of $\varepsilon''$ decreases. At higher temperatures $\varepsilon''$ increases with frequency up to 27 GHz, where all the curves cross each other and thereafter large amplitude fluctuations are observed, which may again be attributed to vibrational peaks due to major contribution coming from water.

### 4.4.7 Permittivity values for pomegranate juice

In Fig. 4.17, the variation of $\varepsilon'$ for pomegranate juice with frequency has been shown at different temperatures (30°C - 60°C). It is observed that at all temperatures $\varepsilon'$ decreases with increasing frequency. It is also observed that the $\varepsilon'$-$f$ curves at 30°C and 40°C, intersect to each other at frequency about 7 GHz, while the curves at all temperatures, intersect at frequency about 11.5 GHz. Thus, the $\varepsilon'$-$f$ curves for different temperatures intersect each other somewhere in the frequency
region \((7 \text{ GHz} \leq f \leq 11.5 \text{ GHz})\). These curves show dielectric dispersion with respect to this intersection frequency. Below this frequency region \((f < 7 \text{ GHz})\) \(\varepsilon'\) decreases with increasing temperature whereas above this frequency region \((f > 11.5 \text{ GHz})\) \(\varepsilon'\) increases with increasing temperature may be due to the effect of relaxation frequency. At higher temperatures \((50 – 60^\circ\text{C})\) vibrational peaks are observed for \(f > 17 \text{ GHz}\), which become more prominent in the frequency range \(40 – 50 \text{ GHz}\).

![Graph of dielectric constant vs frequency](image)

**Fig. 4.17 Frequency dependence of the dielectric constant \((\varepsilon')\) of pomegranate juice at indicated temperatures**

In fig 4.18, we display \(\varepsilon'' - f\) curves for pomegranate juice at different temperatures. From this figure it is apparent that at \(30^\circ\text{C}\), \(\varepsilon''\) first increases with frequency, reaches its maximum value at about \(17 \text{ GHz}\) and then slowly decreases with increasing frequency up to \(50 \text{ GHz}\). The curve is quite smooth, showing absence of molecular excitations at this temperature. The maxima in \(\varepsilon''\)-\(f\) curve may correspond to the relaxation frequency at \(30^\circ\text{C}\). As temperature is increased \(\varepsilon''\) at a particular frequency (below \(30 \text{ GHz}\)) is observed to decrease in magnitude.
Fig. 4.18 Frequency dependence of the dielectric loss factor (\(\varepsilon''\)) of pomegranate juice at indicated temperatures

The general nature of \(\varepsilon''-f\) graph at temperatures 40\(^0\)C to 60\(^0\)C is found to be almost similar, i.e., \(\varepsilon''\) at a particular temperature increases with frequency and attain a maximum value in between 20 to 30 GHz (at 20 GHz for 40\(^0\)C, at about 25 GHz for 50\(^0\)C and at 30 GHz for 60\(^0\)C). At 30 GHz the \(\varepsilon''-f\) curves for the three temperatures (40, 50 and 60\(^0\)C) cross each other and above this frequency large amplitude vibration are observed, which become more prominent at higher temperatures. The case of pomegranate differs from the fruits in the sense that now the curve at 30\(^0\)C does not pass through the point of common intersection (30 GHz in this case).

4.4.8 Permittivity of orange juice:

In Fig. 4.19, the variation of \(\varepsilon'\) for orange juice with frequency has been shown at different temperatures (30\(^0\)C-60\(^0\)C). It is observed that \(\varepsilon'\) continuously decreases with increasing frequency at all temperatures. It is also observed that the \(\varepsilon'-f\) curves for at 30\(^0\)C and 40\(^0\)C, intersect each other at frequency about 5.5 GHz, while the curves at 40\(^0\)C, 50\(^0\)C and 60\(^0\)C, intersect each other at frequency about
10.5 GHz. Thus the $\varepsilon' - f$ curves for different temperatures intersect each other somewhere in the frequency region ($5.5 \text{ GHz} \leq f \leq 10.5 \text{ GHz}$).

![Graph showing frequency dependence of dielectric constant ($\varepsilon'$) of orange juice at indicated temperatures.](image)

**Fig. 4.19 Frequency dependence of the dielectric constant ($\varepsilon'$) of orange juice at indicated temperatures**

These curves show dielectric dispersion according to the intersect point in this frequency region. This region almost overlaps the range of relaxation frequencies which has been reported to be from 8.8 GHz to 11.7 GHz by Kuang and Nelson (1997) at 23°C. Below this frequency region ($f < 5.5 \text{ GHz}$) $\varepsilon'$ decreases with increasing temperature whereas above this frequency region ($f > 10.5 \text{ GHz}$) $\varepsilon'$ increases with increasing temperature may be due to the effect of relaxation frequency. The range of frequencies ($5.5 \text{ GHz} \leq f \leq 10.5 \text{ GHz}$) obtained for orange 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 i.e., 2.45 GHz but lower than the relaxation frequency of water, which is 17.11 GHz at 20°C. Also the $\varepsilon' - f$ curves at 30 and 40°C are found to be quite smooth but for 50°C some fluctuations are observed at frequencies 45 – 50 GHz and similar behavior is also observed at 60°C at frequencies above 35 GHz, but these effects obtained at high temperatures and high frequencies are less prominent.
as compared to water. This is due to the fact that orange juice has high citrus nature, which suppresses the water activity at higher temperatures.

In Fig. 4.20, we display $\varepsilon'' - f$ curves for orange at different temperatures. It is observed that at low temperature ($30^\circ C$) $\varepsilon''$ shows behavior similar to that observed in other fruit juices, particularly to that in pomegranate juice. At this temperature the maxima in $\varepsilon''$-f curve is observed at about 17.0 GHz, which may be due to the relaxation frequency of orange being close to this frequency.

![Image](image-url)

**Fig. 4.20 Frequency dependence of the dielectric loss factor ($\varepsilon''$) of orange juice at indicated temperatures**

As the relaxation frequency is increased with increasing temperature, so in the present study the position of maxima at 17.0 GHz at $30^\circ C$ may be justified. In the lower frequency range (1 -2.5 GHz) a different feature is observed i.e., the $\varepsilon''$-f curves pass through a minima. Below the minima frequency $\varepsilon''$ of orange juice increases with increasing temperature whereas above the minima frequency $\varepsilon''$ decreases on increasing the temperature. This is may be due to the fact as in the frequency range (1-2.5 GHz) the ionic component in orange juice increases with increase in temperature and may dominant the dipole loss. This results in to an increase in dielectric loss with increase in temperature (Mudgett et al., 1980). This shows the acidic nature of orange juice. At
higher temperatures (40 – 60°C), the value of $\varepsilon''$ increases with frequency for all these temperatures, acquire a maximum value and then the curves for these temperatures cross each other at about 32 GHz. Above this frequency we observe fluctuations in $\varepsilon''$-f curves for all the three temperatures.

**Table 4.5 Dielectric parameters of Orange**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Sample</th>
<th>Frequency (GHz)</th>
<th>30°C</th>
<th>40°C</th>
<th>50°C</th>
<th>60°C</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\varepsilon'$</td>
<td>$\varepsilon''$</td>
<td>$\varepsilon'$</td>
<td>$\varepsilon''$</td>
<td>$\varepsilon'$</td>
<td>$\varepsilon''$</td>
</tr>
<tr>
<td>1.</td>
<td>Juice</td>
<td>2.0</td>
<td>72.14</td>
<td>12.51</td>
<td>70.26</td>
<td>11.83</td>
<td>68.16</td>
</tr>
<tr>
<td>2.</td>
<td>Solid</td>
<td>1.8</td>
<td>70.7</td>
<td>14.8</td>
<td>68.6</td>
<td>13.9</td>
<td>65.6</td>
</tr>
<tr>
<td>3.</td>
<td>Juice</td>
<td>1.0</td>
<td>74.41</td>
<td>12.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Solid</td>
<td>1.0</td>
<td>72.0</td>
<td>14.0</td>
<td>(25°C)</td>
<td>(25°C)</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Juice</td>
<td>2.50</td>
<td>71.15</td>
<td>13.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Solid</td>
<td>2.45</td>
<td>69.0</td>
<td>16.0</td>
<td>(23°C)</td>
<td>(23°C)</td>
<td></td>
</tr>
</tbody>
</table>

In Table 4.5 we compare the present values of dielectric parameters of orange juice at certain frequencies and temperatures with the values reported for solid orange by other workers. It may be observed from the table that present values of $\varepsilon'$ and $\varepsilon''$ for orange juice at 2 GHz are in good agreement with the values reported by Wang et al. (2003) at 1.8 GHz at all temperatures from 30 to 60°C. Also the present values of $\varepsilon'$ for orange juice at 1 GHz and 2.5 GHz and temperature 30°C are found to be in fair agreement with the values reported by Nelson (2003) for 1GHz (25°C) and 2.45 GHz at 23°C respectively. The present value of $\varepsilon''$ for orange juice at frequencies 1 and 2.50 GHz and temperature 30°C are found to be slightly lower than the values reported by Nelson (2003) at frequencies 1GHz and 2.45 GHz respectively at temperature 23°C in solid phase. The small difference observed in $\varepsilon''$ values in the two sets of data may be considered due to different states of samples used in two studies. In the present study samples were taken in liquid (juice) state, whereas Wang et al. and Nelson use the samples in solid state.
4.4.9 Permittivity of sweet lime juice:

In Fig. 4.21, the variation of $\varepsilon'$ with frequency is shown for temperatures 30°C to 60°C over the frequency range 1 GHz to 50 GHz for fresh juice of sweet lime. As apparent from Fig. 4.21, the $\varepsilon'$-f curves sweet lime show behavior similar to that of orange juice, because both juices have salty nature. $\varepsilon'$ decreases continuously with increasing frequency at all temperatures. It is also observed that the $\varepsilon'$-f curves at 30°C and 40°C, intersect each other at frequency about 7.5 GHz, while the curves at 50°C and 60°C, intersect each other in the frequency region about 10 to 12.5 GHz. Thus, the $\varepsilon'$-f curves for different temperatures intersect each other somewhere in the frequency region ($7.5 \text{ GHz} \leq f \leq 12.5 \text{ GHz}$). These curves show dielectric dispersion with respect to this intersection frequency region. Below this frequency region ($f < 7.5 \text{ GHz}$) $\varepsilon'$ decreases with increasing temperature whereas above this frequency region ($f > 12.5 \text{ GHz}$) $\varepsilon'$ increases with increases temperature may be due to the effect of relaxation frequency.

At higher frequencies (45 – 50 GHz) and at higher temperatures (50- 60°C) some vibrational peaks are observed due to molecular stretching and librations, which are more pronounced in sweet lime juice as compared to orange juice.

![Graph of dielectric constant vs frequency for sweet lime juice](image)

**Fig. 4.21 Frequency dependence of the dielectric constant ($\varepsilon'$) of sweet lime juice at indicated temperatures**
In Fig. 4.22, we display $\varepsilon''$-$f$ curves for sweet lime juice at different temperatures. The general behaviour of these curves is similar to those of orange juice except that at higher frequency (35-50 GHz) and higher temperatures (40 - 60°C), for which now we obtain vibrational peaks of larger magnitude. For sweet lime the $\varepsilon''$-$f$ curve at 30°C is almost smooth, it shows a maxima at about 17 GHz. The curves at other three temperatures cross each other at about 29 GHz, the maxima in the 40°C curve being at about 24 GHz. The curve at 50°C and 60°C do not come down after attaining a maximum value but show fluctuations about nearly constant or slightly increasing average value of $\varepsilon''$. In the lower frequency range (1 – 2.5 GHz) a noteworthy feature observed in sweet lime juice, which is similar as orange juice, is that $\varepsilon''$-$f$ curve passes through a minima and below the minima frequency $\varepsilon''$ increases with increasing temperature, whereas above this frequency $\varepsilon''$ decreases on increasing the temperature.

![Dielectric loss factor vs Frequency](image)

**Fig. 4.22** Frequency dependence of the dielectric loss factor ($\varepsilon''$) of sweet lime juice at indicated temperatures

This is may be due to the fact as in the frequency range (1 - 2.5 GHz) the ionic component in orange juice increases with increase in temperature and may dominant the dipole loss. This results in to an increase in dielectric loss with increase in temperature (Mudgett et al., 1980).
4.4.10 Permittivity of Lemon juice:

In Fig. 4.23, the variation of $\varepsilon'$ with frequency is shown for temperatures 30°C to 60°C over the frequency range 1 GHz to 50 GHz for fresh juice of lemon. It is observed that at all temperatures $\varepsilon'$ decreases continuously with increasing frequency. It is also observed that the $\varepsilon'$-$f$ curves for at 30°C and 40°C, intersect each other at frequency about 8 GHz, while the curves at 50°C and 60°C, intersect each other at frequency about 10 GHz. Thus, the $\varepsilon'$-$f$ curves for different temperatures intersect each other somewhere in the frequency region (8 GHz ≤ $f$ ≤ 10 GHz). These curves show dielectric dispersion with respect to this intersection frequency region (8 GHz ≤ $f$ ≤ 10 GHz). This region almost overlaps the range of relaxation frequencies which has been reported to be from 10.9 GHz to 13.6 GHz by Kuang and Nelson (1997) at 23°C. Below this frequency region ($f < 8$ GHz) $\varepsilon'$ decreases with increasing temperature whereas above this frequency region ($f > 10$ GHz) $\varepsilon'$ increases with increasing temperature. The range of frequencies (8 GHz ≤ $f$ ≤ 10 GHz) obtained for lemon 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 i.e., 2.45 GHz but lower than the relaxation frequency of water, which is 17.11 GHz at 20°C.

![Figure 4.23 Frequency dependence of the dielectric constant ($\varepsilon'$) of lemon juice at indicated temperatures.](image)
At higher temperatures (40 – 60°C) and at higher frequencies (45 – 50 GHz), some small vibrational peaks are observed in the $\varepsilon'$-$f$ curves, but at 60°C the vibrational peaks are rather suppressed. This is because of the fact that lemon juice is more acidic. It has citric acid whose molecules influences the water activity very much and suppresses vibrational peaks at high temperatures in this frequency range.

In Fig. 4.24, we display $\varepsilon''$–$f$ curves for lemon juice at different temperatures. At temperature (30°C), we obtain almost a smooth $\varepsilon''$-$f$ curve, having a peak value at about 17 GHz, which may be considered to be arise due to the relaxation frequency. Kuang and Nelson (1997) reported the value of relaxation frequency for lemon juice at 23°C to be 13.6 GHz. As the relaxation frequency increases with temperature, we may expect that at 30°C it will be close to frequency of maxima, i.e., 17 GHz. In the lower frequency range (1- 2.5 GHz) $\varepsilon''$-$f$ curve passes through a minima and below the minima frequency $\varepsilon''$ increases with increasing temperature, whereas for frequencies above the minima frequency a reverse trend is observed, i.e., $\varepsilon''$ decreases with increase in temperature. This feature is observed for the juices which have salty nature, as such this is in accordance with the statement made by Mudgett et al. (1980) in the frequency range (1- 2.5 GHz).
At 40°C and 50°C \( \varepsilon'' \) increases steadily with frequency, show almost a saturation state at about 25 GHz and cross each other and the curve at 60°C at about 30 GHz. Above this frequency strong vibrational peaks are observed at these temperatures. At 60°C however not much oscillations are obtained, rather the curve shows a maxima at about 43 GHz, there after the value of \( \varepsilon'' \) decreases. It means lemon juice shows a different trend at temperature (60°C), which may be due to dissolved salt ingredients and under their influence water activity is suppressed.

### Table 4.6 Dielectric parameters for lemon juice

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Frequency</th>
<th>Temperature</th>
<th>( \varepsilon' )</th>
<th>( \varepsilon'' )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.50</td>
<td>30°C</td>
<td>71.70</td>
<td>15.50</td>
<td>Present study</td>
</tr>
<tr>
<td>2</td>
<td>2.45</td>
<td>23°C</td>
<td>71</td>
<td>14</td>
<td>Nelson et al. (1994)</td>
</tr>
</tbody>
</table>

In Table 4.6 we compare dielectric parameters of lemon juice obtained from the present study at 2.50 GHz and temperature 30°C with the values reported by Nelson et al. (1994) for lemon juice at 2.45 GHz and temperature 23°C. It is observed that the present values show excellent agreement with the values reported by Nelson et al. (1994).

#### 4.4.11 Permittivity of Onion juice:

In Fig. 4.25, the variation of \( \varepsilon' \) with frequency is shown for temperatures 30°C to 60°C over the frequency range 1 GHz to 50 GHz for fresh juice of onion. It is observed that at all temperatures \( \varepsilon' \) decreases continuously with increasing frequency. It is also observed that the \( \varepsilon'-f \) curves for at 30°C and 40°C, intersect each other at frequency about 6 GHz, while the curves at 40°C, 50°C and 60°C, intersect each other at frequency about 9.5 GHz. Thus, the \( \varepsilon'-f \) curves for different temperatures intersect each other somewhere in the frequency region (6 GHz \( \leq f \leq \) 9.5 GHz). These curves show dielectric dispersion with respect to this intersect frequency region. Below the region of dielectric dispersion, \( \varepsilon' \) decreases with increasing temperature and above the region of dielectric dispersion, \( \varepsilon' \) increases with increasing temperature may be due to the effect of relaxation frequency. The general behavior of the \( \varepsilon'-f \) curves for onion juice is similar to that of sweet lime.
Small amplitude vibrational peaks are now obtained at higher temperatures (50-60°C) and frequencies above 44 GHz, which suggests that there is sufficient amount of dissolved salt molecules in onion juice. A small peak observed at temperature 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 librations in presence of salts.

![Graph showing frequency dependence of dielectric constant (ε') of onion juice at indicated temperatures.](image)

**Fig. 4.25 Frequency dependence of the dielectric constant (ε') of onion juice at indicated temperatures**

In Fig. 4.26, we display ε'' – f curves for onion juice at different temperatures. The general behavior of these curves is similar to those of sweet lime (Fig. 4.22). At 30°C temperature, 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 be arise due to the relaxation frequency. Kuang and Nelson (1997) reported the value of relaxation frequency for white onion at 23°C to be 15.2 GHz. 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 ε''-f curve. At frequencies greater than 15.5 GHz, ε'' is found to decrease steadily, except of small variations around 50 GHz. At lower frequency range (1- 2.5 GHz) ε''-f curves show a minima and below the minima frequency ε'' increases with increasing temperature. In lower frequency range (1- 2.5
GHz) $\varepsilon''$-f curves show a minima and below the minima frequency $\varepsilon''$ increases with increasing temperature. This feature is observed for the juices which have salty nature and this is in accordance with the statement reported by Mudgett et al. (1980) in the frequency range (1-2.5 GHz). At 40°C also a graph similar to that at 30°C is obtained, but with the difference that now maxima of $\varepsilon''$-f curve is obtained at about 22 GHz and above this frequency $\varepsilon''$ decreases more slowly as compared to that of 30°C. At higher temperatures (50 – 60°C) the $\varepsilon''$-f curves acquire a uniform average value at 50°C, while peak increasing at 60°C. The appearance of vibrational peaks at higher temperatures and in higher frequency range is due to water playing a major role.

![Graph showing dielectric loss factor vs frequency at different temperatures](image)

**Fig. 4.26 Frequency dependence of the dielectric loss factor ($\varepsilon''$) of Onion juice at indicated temperatures**

**Table 4.7: Dielectric parameters of onion**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Frequency</th>
<th>Temperature</th>
<th>$\varepsilon'$</th>
<th>$\varepsilon''$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.50</td>
<td>30°C</td>
<td>70.77</td>
<td>16.41</td>
<td>Present study</td>
</tr>
<tr>
<td>2</td>
<td>2.45</td>
<td>23°C</td>
<td>64</td>
<td>14</td>
<td>Nelson et al. (1994)</td>
</tr>
</tbody>
</table>
In Table 4.7 we compare the dielectric parameters of onion juice obtained from the present study at 2.50 GHz and temperature 30°C with the values reported by Nelson et al. (1994) at 2.45 GHz and temperature 23°C. It is observed that there is a fair agreement between the two sets of data, the present values being slightly higher than the values reported by Nelson et al. (1994). The difference in $\varepsilon'$ and $\varepsilon''$ values may be due to different varieties of onion used in the experiments.

4.4.12 Permittivity values for Tomato juice

In Fig. 4.27, the variation of $\varepsilon'$ with frequency is shown for temperatures 30°C to 60°C over the frequency range 1 GHz to 50 GHz for fresh juice of tomato. The general behavior of $\varepsilon'$-f curves for tomato juice is similar to that of onion juice (Fig. 4.25). It is observed that at all temperatures $\varepsilon'$ decreases continuously with increasing frequency. It is also observed that the $\varepsilon'$-f curves at all temperatures, intersect to each other at frequency about 10 GHz. These curves show dielectric dispersion below and above the frequency 10 GHz. Below the region of dielectric dispersion, $\varepsilon'$ decreases with increasing temperature and above the region of dielectric dispersion, $\varepsilon'$ increases with increasing temperature may be due to the effect of relaxation frequency. At 50°C also only small vibrational peaks are obtained above 40 GHz, whereas at 60°C the vibrational peaks are prominent and similar to those of water, which suggests that though water plays an important role in the dielectric properties of tomato juice, a sufficient amount of dissolved salt molecules are also present in tomato juice lowering activity of water at lower temperatures (say 50°C). Small peaks observed at high temperature (50 - 60°C) in the frequency region (40-50 GHz), may be considered to arise due to the molecular libration in tomato juice.

In Fig. 4.28, we display $\varepsilon''$ – f curves for tomato juice at different temperatures. At low temperature (30°C), the $\varepsilon''$-f curve starts from a minima at about 2.5 GHz and then $\varepsilon''$ 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 other cases.
Fig. 4.27 Frequency dependence of the dielectric constant ($\varepsilon'$) of tomato juice at indicated temperatures

Fig. 4.28: Frequency dependence of the dielectric loss factor ($\varepsilon''$) of tomato juice at indicated temperatures
Above this frequency $\varepsilon''$ decreases with frequency and rapid oscillations are obtained in the frequency range above 40 GHz. At 40$^0$C also we obtain a similar curve but now maxima position shifts to higher frequencies. At higher temperatures (50-60$^0$C) we obtain rapid oscillations in the curves at frequencies above 29 GHz, where the curves at all temperatures cross each other. In the lower frequency range (1-2.5 GHz) $\varepsilon''$-f curves show a minima. At frequencies below the minima $\varepsilon''$ increases with increasing temperature, where as frequencies above the minima frequency a reverse trend is observed, i.e., $\varepsilon''$ decreases with increase in temperature. This feature observed in the frequency range (1 - 2.5 GHz), for the juices which have salty nature and this is in accordance with the statement made by Mudgett et al. (1980).

### 4.4.13 Permittivity of Potato juice

![Graph showing frequency dependence of the dielectric constant ($\varepsilon'$) of potato juice at indicated temperatures.](image)

**Fig. 4.29 Frequency dependence of the dielectric constant ($\varepsilon'$) of potato juice at indicated temperatures**

In Fig. 4.29, the variation of $\varepsilon'$ with frequency is shown for temperatures 30$^0$C to 60$^0$C over the frequency range 1 GHz to 50 GHz for fresh juice of potato. It is observed that at all temperatures $\varepsilon'$ decreases continuously with increasing frequency. It is also observed that the $\varepsilon'$-f curves for at 30$^0$C and 40$^0$C, intersect to
each other at frequency about 6 GHz, while the curves at 50°C and 60°C intersect each other at frequency 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 i.e., 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 amplitudes 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), presence of carbohydrate is related to stabilization of hydrogen bonding patterns through hydroxyl – water interaction which reduces the effect of water activity. Therefore, small vibrational peaks are obtained for potato juice at higher temperatures (40 – 60°C) and higher frequency (35 – 50 GHz).

In Fig. 4.30, we display ε" – f curves for potato juice at different temperatures. At temperature (30°C), the ε''-f curve starts from a minima at about 2.5 GHz, then ε'' increases with frequency. It acquires a peak value at about 19 GHz, which may be considered to arise 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 temperature 30°C, which lies in the vicinity of the maxima frequency. Beyond this frequency the value of ε'' slowly decreases but ε'' shows strong oscillations in between 30 to 50 GHz. At 40°C also the behavior of ε''-f curve is similar to that of 30°C, but the maxima positions shifts 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.

**Fig. 4.30** Frequency dependence of the dielectric loss factor (ε") of potato juice at indicated temperatures

In the low frequency region minimas are obtained at all temperatures between 1 to 2.5 GHz, the position of minima shifting to higher frequencies side as the temperature increase, as reported by Mudgett et al. (1980). Below minima frequencies ε" increases with increase in temperature, whereas at frequencies above the minima frequency ε" decreases with increase in temperature. At frequency 1 GHz and temperature 60°C, a very high value (= 29.32) of ε" is found. This feature may be attributed to the presence of complex starch in the potato juice. The large amplitude vibration obtained at all the temperatures at frequency above 30 GHz may be attributed to the presence of starch in the potato juice.
Table 4.8: Dielectric parameters for potato juice

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Sample</th>
<th>Frequency (GHz)</th>
<th>Temperature (°C)</th>
<th>ε’</th>
<th>ε”</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Juice</td>
<td>1</td>
<td>30°C</td>
<td>77.79</td>
<td>22.00</td>
<td>Present study</td>
</tr>
<tr>
<td></td>
<td>Solid</td>
<td>1</td>
<td>25°C</td>
<td>62</td>
<td>16</td>
<td>Nelson et al. (1994)</td>
</tr>
<tr>
<td>2</td>
<td>Juice</td>
<td>2.50</td>
<td>30°C</td>
<td>74.35</td>
<td>17.89</td>
<td>Present study</td>
</tr>
<tr>
<td></td>
<td>Solid</td>
<td>2.45</td>
<td>23°C</td>
<td>57</td>
<td>17</td>
<td>Nelson et al. (1994)</td>
</tr>
</tbody>
</table>

In Table 4.8 we compare the present values of dielectric parameters for potato juice at 1.0 and 2.50 GHz (for 30°C) with those reported by Nelson et al. (1994) for solid mass of potato at 1.0 GHz (for 25°C) and 2.4 GHz (for 23°C) respectively. It is observed that the present values of ε’ for potato juice which decrease with frequency, show behavior similar to those reported by Nelson et al. for solid mass of potato. The present values of ε’ are comparatively higher than the values reported by Nelson et al. at both the frequencies. Also the present value of loss factor (ε”) at 1 GHz is higher than that reported by Nelson et al. (1994), but at 2.50 GHz the present value of ε” is in good agreement with the value reported by Nelson at frequency 2.45 GHz and 23°C. The reason for this difference in the present values and those reported by Nelson may be attributed to the difference in the nature of samples used in the two researches. In the present research the dielectric properties of potato juice have been determined whereas Nelson et al. have determined dielectric parameters for potato mass.

4.3.14 Permittivity of Cucumber juice:

In Fig. 4.31, the variation of ε’ with frequency is shown for temperatures 30°C to 60°C over the frequency range 1 GHz to 50 GHz for fresh juice of cucumber. It is observed that at all temperatures ε’ decreases continuously with increasing frequency. The general behavior of these curves is similar to those of orange (Fig. 4.25), but the curves obtained in this case are comparatively smoother. It is also observed that the ε’-f curves for at 30°C and 40°C, intersect to each other at frequency about 7 GHz, while the curves at 50°C and 60°C, intersect each other at
frequency about 12 GHz. Thus, the $\varepsilon'$-f curves for different temperatures intersect each other somewhere in the frequency region ($7 \text{ GHz} \leq f \leq 12 \text{ GHz}$). These curves show dielectric dispersion with respect to this intersection frequency region. Below the region of dielectric dispersion, $\varepsilon'$ decreases with increasing temperature and above the region of dielectric dispersion, $\varepsilon'$ increases with increasing temperature may be due to the effect of relaxation frequency. Also small vibrations in $\varepsilon'$-f curves for $50^\circ C$ and $60^\circ C$ may be noticed in the frequency region between 35-50 GHz, which may arise for reasons similar to those explained earlier.

![Graph showing dielectric constant vs frequency for different temperatures](image)

**Fig. 4.31** Frequency dependence of the dielectric constant ($\varepsilon'$) of cucumber juice at indicated temperatures

In Fig. 4.32, we display $\varepsilon''$ – f curves for cucumber juice at different temperatures. At low temperature ($30^\circ C$), the curve starts from a minima at about 1 GHz, it increases with frequency and then a peak value is found at frequency about 19 GHz, which may arise due to the relaxation frequency. Kuang and Nelson (1997) reported the value of relaxation frequency for cucumber juice at $23^\circ C$ which is 17.6 GHz. This study shows that the relaxation frequency of cucumber juice is 19 GHz at temperature $30^\circ C$ which is close to the frequency of maxima.
Fig. 4.32 Frequency dependence of the dielectric loss factor ($\varepsilon''$) of cucumber juice at indicated temperatures

Above this frequency $\varepsilon''$ steadily falls down and a smooth curve is obtained. In the lower frequency range (1-2.5 GHz) $\varepsilon''$-f curves show a minima. Below the minimum frequency $\varepsilon''$ increases with increasing temperature whereas above this frequency $\varepsilon''$ decreases on increasing temperature. In the lower frequency range (1-2.5 GHz) $\varepsilon''$-f curves show a minima. Below the minimum frequency $\varepsilon''$ increases with increasing temperature whereas above this frequency $\varepsilon''$ decreases on increasing temperature. At higher temperatures (40 – 60°C) and at higher frequencies (35 – 50 GHz) some vibrational peaks are obtained which may be due to the ingredients dissolved in the cucumber juice. In this case water also plays an important role.

4.4 Conclusion

The dielectric properties of fresh juices of fruits and vegetables can be efficiently measured by E8364C PNA network analyzer and 85070E coaxial probe in the frequency range 1 GHz to 50 GHz. The present values of $\varepsilon'$ and $\varepsilon''$ are found to be in good agreement with the values reported by other authors, and are also in agreement with the trend described by Nelson et al. (1994). These measurements
may be useful in dielectric heating applications and may serve as background knowledge in exploring the dielectric properties of fruits and vegetables for potential new quality sensing applications.