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The Analysis of Dielectric Constant, Loss Factor and Q-Factor of Selected Fruits at Microwave Frequency Range

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Authors' contributions

This work was carried out in collaboration among all authors. Author JTI designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AAM and NSA managed the analyses of the study. Authors ZEA and STK managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The dielectric constant, dielectric loss factor and Q-Factor of orange, red and green apples were studied at Microwave frequency range. An algorithm was written using the Debye equations and the interactive problem-solving environment of Maple-18 was used to generate results for the dielectric constant, loss factor and quality factor. The variation in the dielectric constant, loss factor and Q-factor as both frequency and temperature changes respectively within $0.01 \leq f_r \geq 4GHz$ and $20^0C \leq T \geq 60^0C$ range were shown graphically. The dielectric constant of all the fruits were higher at lower frequencies, it then decreases continuously as frequency increases. On the other hand, the loss factor of this fruits were small at lower frequencies but increased to its peak before decreasing continuously for all temperatures. Interestingly, the fruits' Q-Factor were higher at lower frequencies and temperatures but decreases rapidly as the frequency increases. The contribution

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of the space charge, orientation, ionic and electronic polarizations to the dielectric constant, dielectric loss factor and Q-Factor of these fruits at lower frequency and higher frequency were discussed. The effect of the excess sugar and water content on the dielectric constant, loss factor and Q-Factor attributed to the appearance of vibrational peaks was also discussed. This work hereby provides a guidance in developing new microwave processes.

Keywords: Dielectric constant; loss factor; Q-Factor; orange; red apple; green apple; microwave; Maple-18; Debye equations.

1. INTRODUCTION

The dielectric materials are electrical insulating materials that can be polarized by an application of the electric field. Whenever a dielectric material is placed in an electric field, electric charges do not flow through the material as they do in the conductors. Instead a slight shift from their average equilibrium positions is observed thereby causing dielectric polarization in those materials. Hence dielectric materials are those substances same as insulators. However, unlike the insulating materials, they do allow the flow of electron through them when subjected to an external electric field. The dielectric properties of materials serve as a measure of interaction of these materials with electromagnetic radiation and provide useful information about their molecular structure.

The dielectric properties are useful tool especially in determining the interactions of materials and the electromagnetic energy. The dielectric studies have major applications in the communication systems, electronics and food industries which are related to the novel microwave or radio frequency heating treatment. The dielectric constant on radiation efficiency of embedded antenna has been investigated both analytically and numerically, with dielectric constant $\varepsilon' = 1$ the highest radiation efficiency of implanted antennas can be obtained which is desirable for applications of materials intended for use as insulator [1,2]. Tiras, Dede, and Aitay [3] suggested that the moisture content and especially the dipole rotation and the conductivity movements of the molecules in free water content of the food are some of the most critical factors influencing the dielectric properties of food materials.

Fruits and vegetables usually contain large amount of water content especially when compared with grains. The water molecules are polar in nature hence they contribute substantially to the polarization of food molecules when placed in an alternating electric field [4]. The dielectric properties of food materials are thus, those electrical properties which are responsible for the polarization of food molecules and measure the interaction of food with electromagnetic fields [5].

The non-destructive testing techniques have been used in both agriculture and food industry successfully [6]. These techniques are found to be useful to producers, handlers and processors for non-destructive determination of moisture, quality and other related characteristics of agricultural products, food items, maturity and quality sensing in fresh fruits and vegetables [7].

Dielectric spectroscopy, a tool that describes the dielectric properties of materials as a function of frequency, has been successfully used for examining the behaviour of those materials in radio and microwave frequency regions of electromagnetic spectrum [8]. Today, the electrical properties of food materials are finding increasing applications in agriculture and food processing industries [9].

The dielectric spectroscopy is also important in processes like moisture measurement in crops, protection of seeds and destruction of insects in fruits and nuts by selective heating on one hand and in processing of foods using microwave heating as well as finding better processing conditions leading to better quality of foods on the other hand [10].

The dependence of dielectric properties of several types of fruits and vegetables on temperature and frequency has been investigated [11,12,13,14,15]. However, the physical changes that takes place during the process such as moisture loss and protein denaturation has an effect on the dielectric properties of the fruits which could result in either the increase or decrease in the dielectric constant or dielectric loss factor of the fruit and vice versa as the case may be, affecting the taste and quality of the fruits [4,16].

In response to this problem, this study proposes to evaluate the Q-factor of the fruits at microwave frequency range to serve as a guide to food technologist and engineers in their attempt to improve the quality of microwave foods, to design microwavable foods and to develop new microwave processes.

2. THEORETICAL FRAMEWORK

Some basic atomic models used earlier to depict the behaviour of materials in alternating field revealed that the dielectric constant under these conditions is a complex quantity. The imaginary part of this complex dielectric constant determines the dielectric losses of the material.

When an alternating voltage $\mathrm{V} = \mathrm{Re}(\mathrm{V_0} e^{j\omega t})$ is placed across dielectric capacitor plates, a charging current I_c will flow provided that the dielectric is a perfect one (i.e. conduction$= 0$). Thus in an ideal dielectric, the current is

$$\mathrm{I} = \mathrm{I_c} = \mathrm{j}\omega\mathrm{CV} = \mathrm{j}\omega\varepsilon_s\mathrm{C_oV} \tag{1}$$

Where ε_s is the static dielectric constant but practically, an in- phase component of current will also appear. Such current is entirely due to dielectric medium and is a property of it. Therefore, the dielectric constant ε_s, in alternating fields, is replaced by a complex dielectric constant ε^* such that:

$$\varepsilon^* = \varepsilon' - \mathrm{j}\varepsilon'' \qquad \text{(by convention)} \tag{2}$$

Where $= \sqrt{-1}$. Dielectric constant ε' accounts for the ability of the material to store electric energy. Dielectric loss factor ε'' accounts for the loss energy dissipative mechanisms in the material hence explaining the conversion of microwave (electromagnetic) energy into thermal energy:

$$Q = 2\pi\varepsilon_0\varepsilon'' \oint E^2 \tag{3}$$

Where Q is the converted thermal energy per unit volume (w/m^3) and E is the electric field instantaneous intensity (V/m).

The equation (2) have been used to obtain the real ε' and imaginary parts ε'' of the Debye relaxation equation as thus:

$$\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)}{1 + (\omega\tau)^2} \tag{4}$$

And the imaginary part

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + (\omega\tau)^2} \tag{5}$$

The details of these derivations is shown in [17], [18].

3. METHODS

The experimental values of static permittivity ε_s and electrical conductivity σ of orange, green and red apples were adapted from [19]. The relaxation time τ and the complex permittivity were computed from the following equations:

$$\tau = \frac{4\pi\eta a^3}{kT} \tag{6}$$

Boltzmann constant and T is the temperature. The electrical conductivity and the complex permittivity are related by this expression:

$$\varepsilon'' = \frac{\sigma}{\omega\varepsilon_o} \tag{7}$$

Where ω is the angular frequency and ε_o is the permittivity of free space [20]. The equations (3), (4), (5), (6) and (7) were used in an interactive problem-solving environment of Maple-18. The results generated for this work are shown below:

4. RESULTS AND DISCUSSION

The results for dielectric constant, loss factor and Q-Factor of orange, red and green apple as a function of relaxation frequency at different temperatures are shown in the figures below:

The dielectric properties of orange, red and green apples and their Q-Factor at different frequency and temperature are studied in this work. The dielectric constant of all the fruits were higher at lower frequencies. The space charge, orientation, ionic and electronic polarizations are major contributors to this higher dielectric constant at lower frequencies [21]. However, the dielectric constant decreases continuously as the frequency increases. The decrease in the dielectric constant at higher frequency is because of the space charge and orientation polarizations that could not keep pace with the fast changes in the frequency. Therefore the disappearance of the space charge and orientation polarizations allows only the ionic and electronic polarizations to contribute to the dielectric constant of these fruits at higher frequencies.

There are however, some sharp increases in the dielectric constant of orange and red apple as the frequency increases. This can be attributed to the level of sugar content in these fruits. Tulasidas et al. [22] observed that materials containing sugar are influenced by the free water hydroxyl groups of the sugar, and therefore the hydrogen bonds are stabilized, giving rise to small amplitude peaks at the vibrational frequencies of such bonds as seeing in both Fig. 1 and Fig. 2. This shows that oranges and red apples contain more sugar than green apples.

The dielectric constant of red apple decreased as the temperature increases in Fig. 2. However, the dielectric constant of both orange and green apple was smaller at 20°C and increased as temperature increases to 30°C (Figs. 1 and 3), then decreased continuously as the temperature increases further. This decrease in the dielectric constant as temperature increases may be due to the presence of moisture content in the fruits. However, as temperature increases, the moisture content in these fruits decreases thereby causing a decrease in the dielectric constant.

The dielectric losses shown in Figs. 4 to 6 were small at lower frequencies and increases to its peak values when the frequency increases. The maximum (peak) values of the loss factor corresponds to the maximum conversion of electromagnetic energy to thermal energy. A material with high loss factor ε'' is easily heated, hence, well for microwave oven. Therefore, some plastic containers with high loss factor should not be used in a microwave oven because they can be melted by the heat of the food inside [23]. The loss factor however decreases steadily after attaining its peaks. There are however, some sharp increases in the loss factor witnessed in orange and sharp decrease in red apple. This sudden increase and decrease (vibrational peak) in orange and red apple may be due to the excess sugar molecules found in orange and red apple.

The dielectric loss factor was also found to be higher at lower temperature and decreases continuously when temperature increases. This decrease in the loss factor as the result of an increase in the temperature may be due to the reduction in moisture content [24]. The higher dielectric constant and small loss factor were responsible for higher quality factor (Q-Factor) obtained at lower frequencies and temperatures. This is because Q-Factor varies directly to the dielectric constant and inversely proportional to the dielectric loss factor. Figs. 7- 9 shows that Q-Factor is higher at lower frequencies and temperatures but decreases quickly as the frequency increases. The Q-Factor however, decreases continuously as both frequency and temperature increases further.

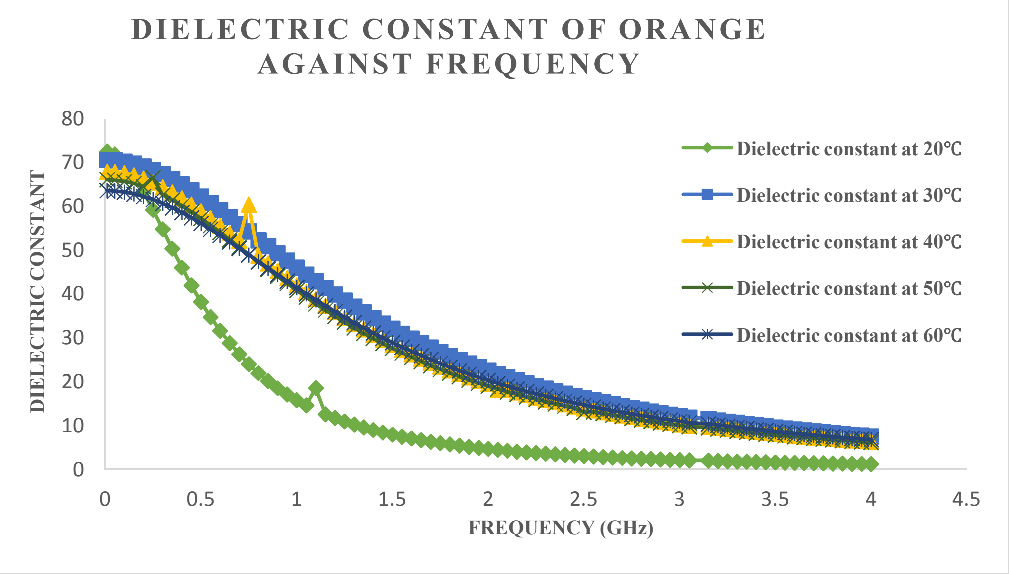

Fig. 1. The graph of dielectric constant at different temperatures against the frequency. The dielectric constant of orange is higher at lower frequencies and decreases steadily as the frequency increases for all temperatures. However, there are some exceptions for certain temperatures. That is, at 40°C and 60°C where there are some sort of increments at 0.75GHz and 1.1GHz respectively

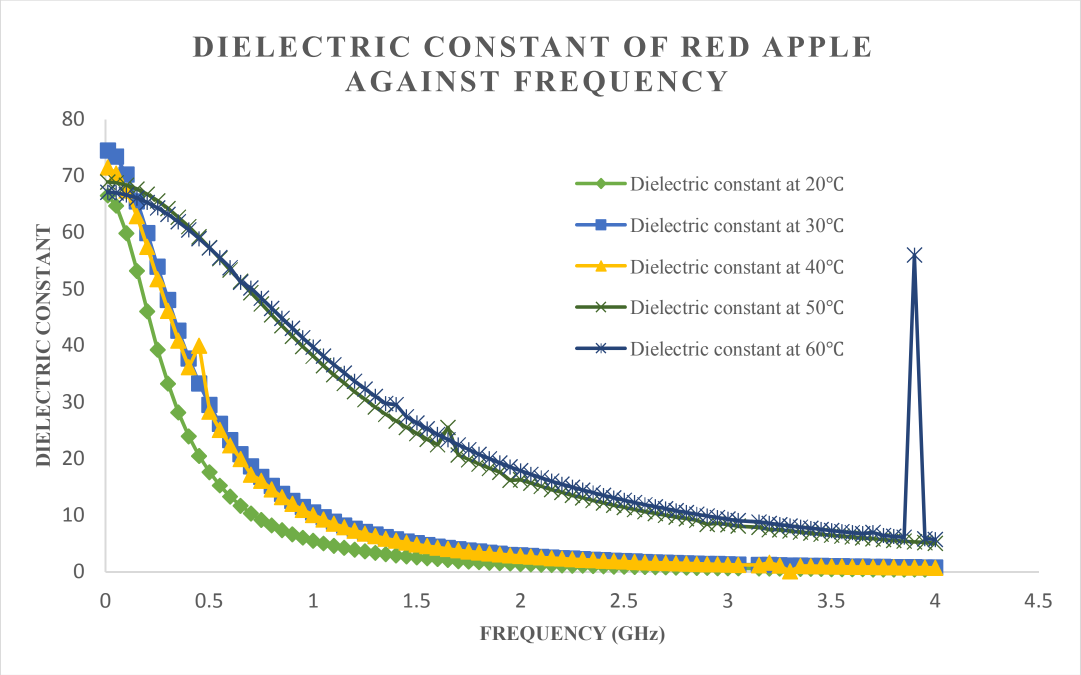

Fig. 2. The dielectric constant of red apple against the frequency. The dielectric constant of red apple at different frequency and temperature also exhibits a similar behaviour as that of orange. There are higher values of the dielectric at lower frequencies and decreases continuously for all temperatures except at 40°C and 60°C where there are sharp increases at 0.45GHz and 3.90GHz

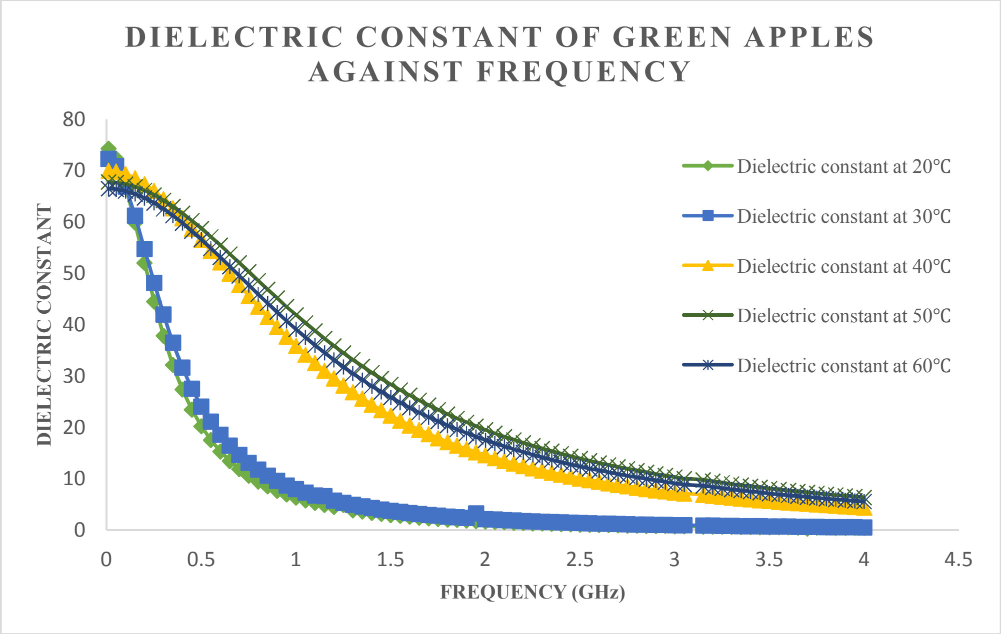

Fig. 3. The dielectric constant of green apple against the frequency. The dielectric constant of green apple are also higher at lower frequencies and decreases steadily for all temperatures. There are no obvious sharp increment observed in this fruit

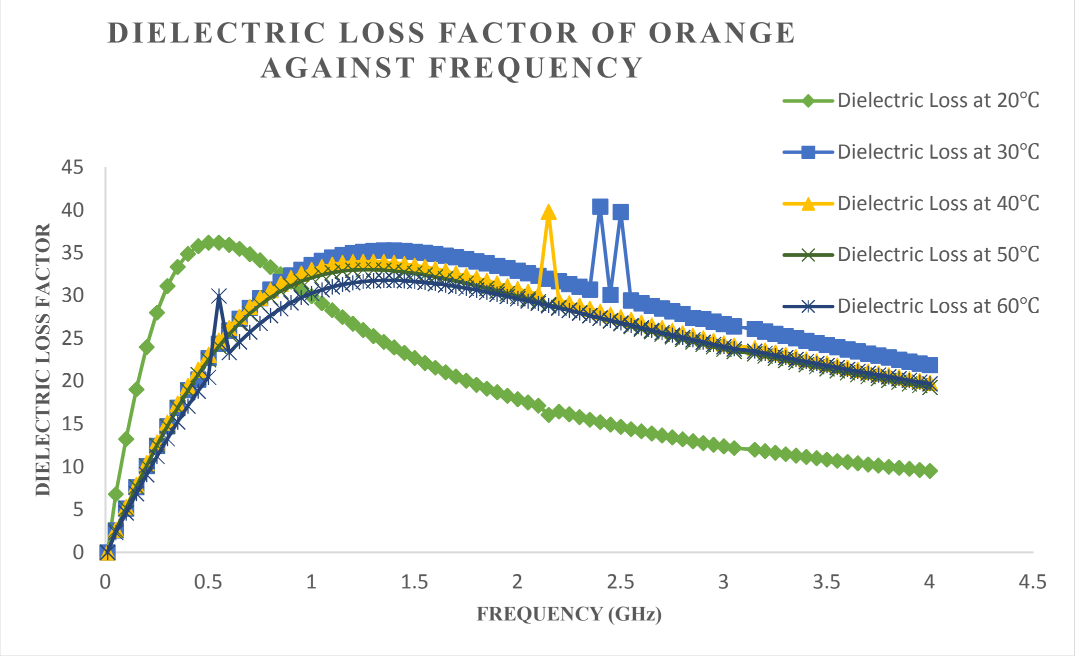

Fig. 4. The dielectric loss factor of orange against the frequency. The loss factor of this fruit is small at lower frequency but increased to its peak before decreasing continuously for all temperatures. There are however, some discrepancies observed at 30°C and 40°C where there are increments at 2.4GHz, 2.5GHz and 2.15GHz

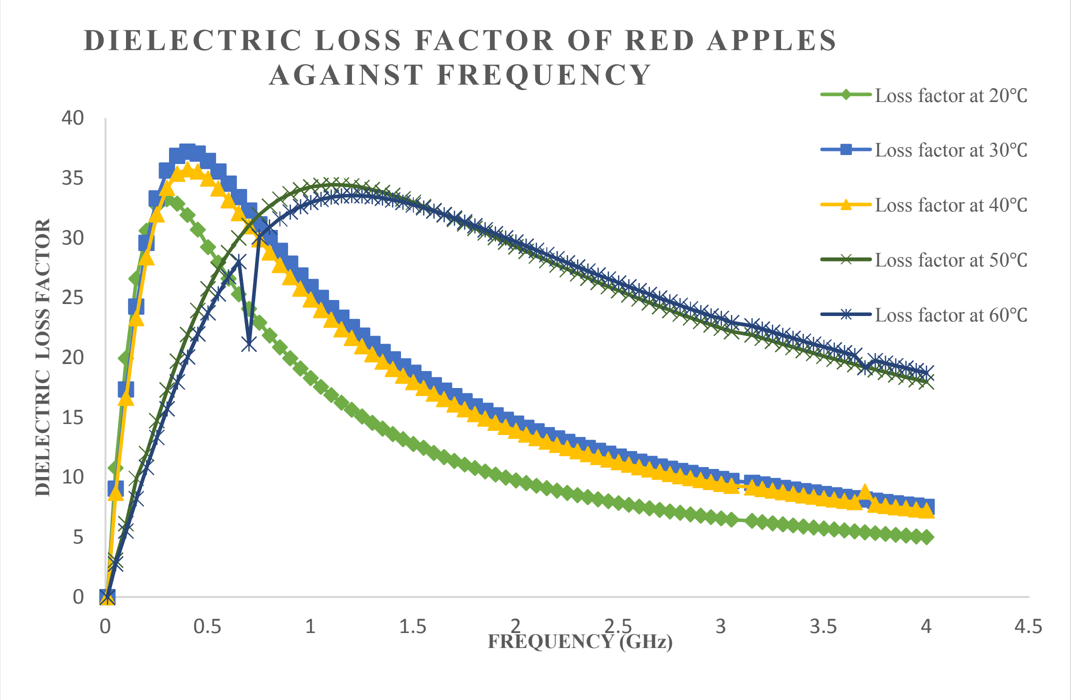

Fig. 5. The dielectric loss factor of red apple against the frequency. The loss factor increases to its peak and decreases steadily for all temperatures except for 60°C where there is a sudden decrease at 0.70GHz

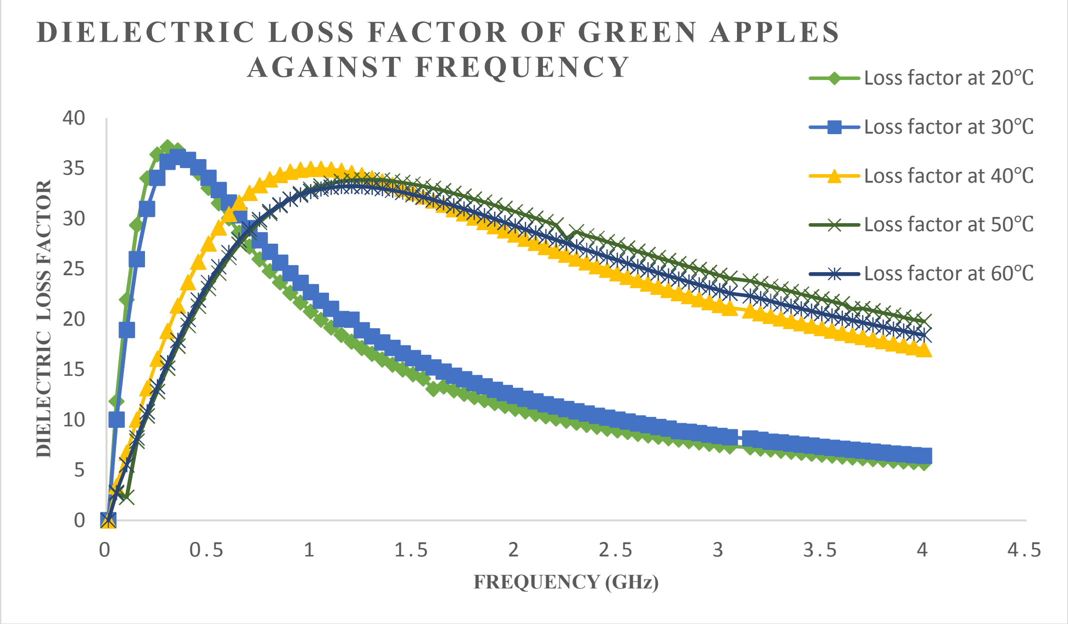

Fig. 6. The dielectric loss factor of green apple against the frequency. The dielectric loss factor of this fruit increases from lower frequency to its peak as the frequency increases. The losses however, continues to decrease steadily after reaching the peak for all temperatures

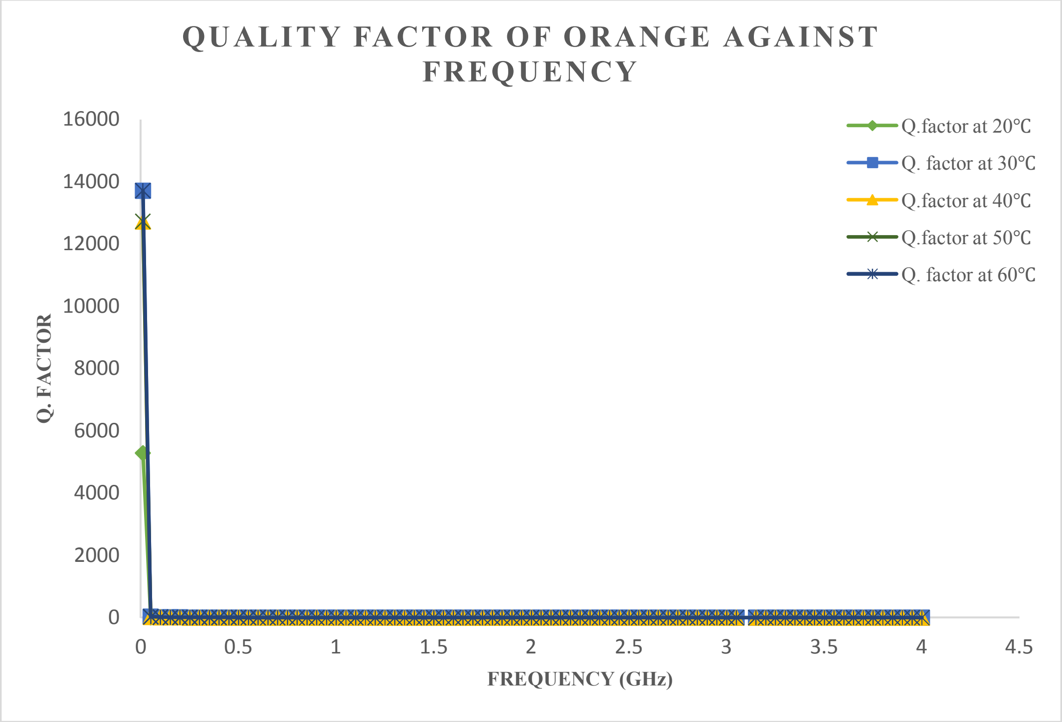

Fig. 7. The quality factor (Q-Factor) of orange against the frequency. The Q-Factor of orange at lower frequencies was very high and decreases sharply as the frequency increased 0.05GHz. The Q-Factor then decreases continuously as the frequency increases beyond 0.05GHz for all temperatures

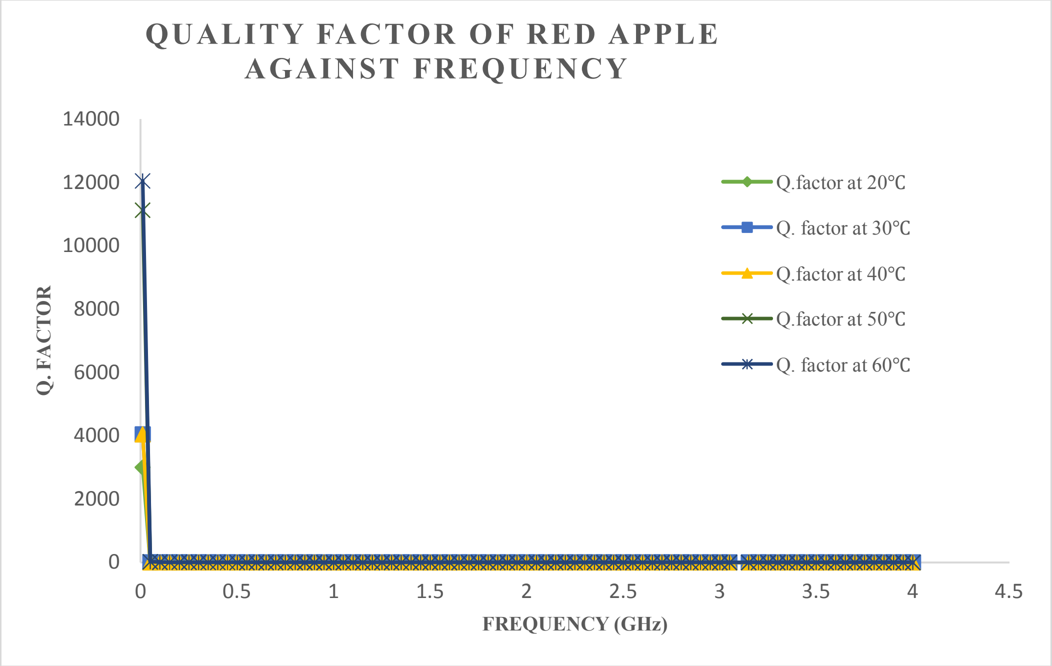

Fig. 8. The Q-Factor of red apple against the frequency is shown in the figure above. The red apple also have similar behaviour as that of orange for all temperatures. A higher Q-Factor at lower frequency, a sharp decrease as the frequency increases and a continuous decrease as the frequency increase further

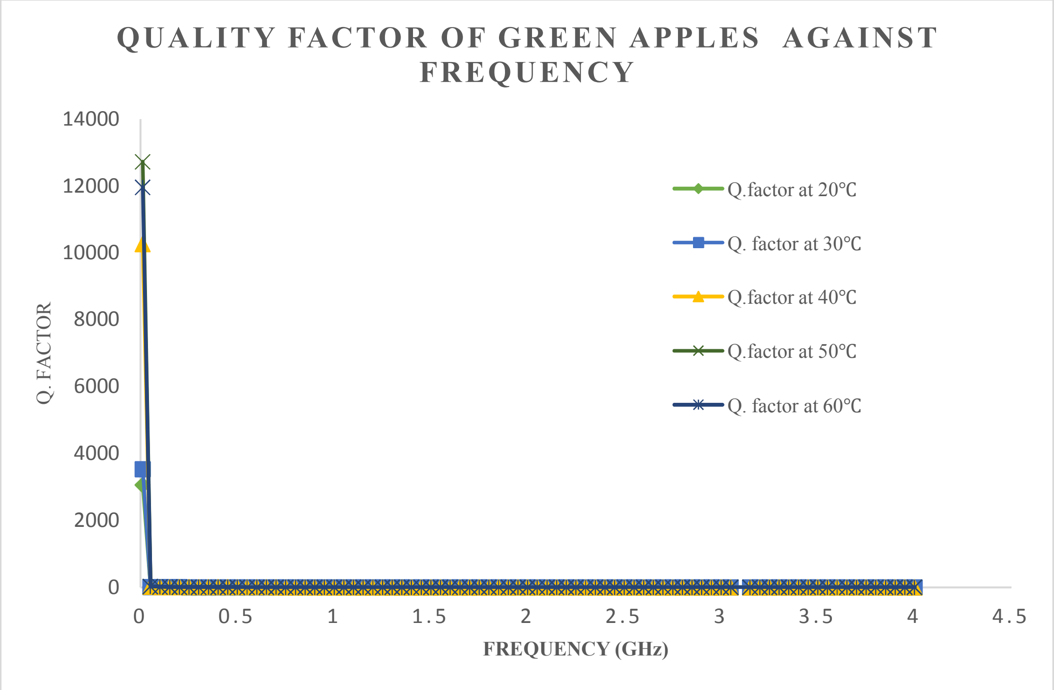

Fig. 9. The Q-Factor of green apple against the frequency. The higher values at lower frequency, sharp decrease as frequency decreases and a steady decrease at further increment in the frequency for all temperatures.

5. CONCLUSION

The dielectric constant, loss factor and Q-Factor of orange, red and green apples were analyzed at microwave frequency range. This work provide suitable data for orange, red and green apples at the frequency range of 0.01GHz to 400GHz and temperature range of 20°C to 60°C. At lower frequencies and temperatures the space charge, orientation, ionic and electronic polarizations contributes to the higher dielectric constant and Q-Factor. The space charge and orientation polarizations disappear as the frequency increases thereby causing the decrease in the dielectric constant and Q-Factor. The loss factor on the other hand, increases from small values at lower frequency and temperature to its maximum values. The values however decreases after attaining the maximum as the frequency increases further. There were however, some few vibrational peaks caused by excess sugar in dielectric constant and loss factor of orange and red apple. This shows that orange and red apple contain more sugar than the green apple. The higher dielectric constant and Q-Factor at higher temperature were due to the water molecules in these fruits. This is evidence as an increase in the temperature causes the decrease in both dielectric constant and Q-Factor.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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