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Dielectric properties of tomatoes assisting in the development of microwave pasteurization and sterilization processes

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ABSTRACT

Dielectric properties of tomatoes crucially affect their heating behaviors in an electromagnetic field and are essential for developing microwave pasteurization and sterilization processes for different tomato products. The open-ended coaxial probe technique was used to determine the dielectric properties of tomatoes over a frequency range of 300–3000 MHz for temperatures between 22 and 120 °C. Three tomato tissues, the pericarp tissue (including the skin), the locular tissue (including the seeds) and the placental tissue were studied separately. The effects of NaCl (0.2 g/100 g) and $CaCl_2$ (0.055 g/100 g) on the dielectric properties of tomatoes were also investigated. The dielectric loss factors were significantly different among the three tomato tissues. However, no significant differences were found in their corresponding dielectric constants. The loss factors of the three tomato tissues decreased with increasing frequency and increased with salts added. Increasing temperature increased the loss factors of the three tomato tissues at 915 MHz, but initially decreased then increased their corresponding values at 2450 MHz. The differences in the loss factors of the three tomato tissues were mainly caused by the difference in ionic conductivity.

1. Introduction

The tomato is one of the most popular vegetables in the United States, second only to potato in terms of crop yield and consumption. The U.S. is one of the world's leading producers of tomatoes, with an annual production of 12–15 million metric tons valued around $10 billion dollars over the last decade (USDA, 2010). Three-fourths of these tomatoes are consumed in processed form, most of which are thermally processed (Lucier & Glaser, 2009). The U.S. consumption of processed tomatoes began a steady climb that accelerated in the late 1980s with the rising popularity of pizza, pasta, and salsa (Lucier & Glaser, 2009). Even with the increase in consumption of fresh tomatoes in recent years, the demand for processed tomatoes remains relatively stable and consistent.

As one of the advanced processing technologies, microwave heating provides a relatively short heating time due to its ability to generate volumetric heating within food materials, and thus has the potential to be an alternative thermal treatment method for processing tomato products. Two frequency bands are allocated by the U.S. Federal Communication Commission (FCC) for microwave heating applications: the 915 MHz band for industrial use and the 2450 MHz band for both industrial and domestic uses. Dielectric properties of food materials which reflect the interaction between the foods and electromagnetic energy are essential for successful design of microwave pasteurization and sterilization processes. The dielectric properties of biological materials include the dielectric constant (ε') which is related to a material's ability to store electric energy when subjected to an electromagnetic field, and dielectric loss factor (ε'') which influences the conversion of electromagnetic energy into thermal energy. They are two elements of material's complex relative permittivity (ε^*) presented as $\varepsilon^* = \varepsilon' - j\varepsilon''$, where $j = \sqrt{-1}$. The dielectric properties of a material can also be used to estimate the thermal energy converted from electric energy at microwave frequencies. If heat loss is negligible, the increase in temperature (ΔT) of the material can be calculated from (Nelson, 1996):

$$Q = \rho C_p \frac{\Delta T}{\Delta t} = 2\pi f \varepsilon_0 \varepsilon'' E^2$$

where C_p is the specific heat of the material (J/kg °C), ρ is the density of the material (kg/m^3), Δt is the time (s), ε_0 (8.8542 × 10^{-12} F/m) is the permittivity of free space or vacuum, E is the strength of electric field (V/m), and f is the frequency (Hz).

Several papers have reported the dielectric properties of fruits and vegetables (Birla, Wang, Tang, & Tiwari, 2008; Feng, Tang, &

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Cavalieri, 2002; Ikediala, Tang, Drake, & Neven, 2000; Nelson, Forbus, & Lawrence, 1994; Seaman & Seals, 1991; Wang, Zhang, Mujumdar, & Jiang, 2011). There is very limited published information related to dielectric properties of tomatoes in a wide temperature range for the two microwave frequencies. Experimental data for those properties are, however, needed for proper design of microwave pasteurization and sterilization processes. Reyes, Heredia, Fito, Reyes, and Andres (2007) obtained the dielectric constant and loss factor of osmotically dehydrated cherry tomatoes measured at 2450 MHz and 20 °C. Ghanem (2010) studied the dielectric properties and penetration depth of tomato juice from 25 to 45 °C at 2450 MHz. Kumar, Coronel, Simunovic, and Sandeep (2008) measured ε' and ε'' of tomato particulates and puree for salsa con queso in a temperature range of 20–130 °C at 915 MHz. However, there is no published data on the dielectric properties of different tomato tissues. For the Roma tomato, the average wet weight percentage of the pericarp tissue (including skin), locular tissue (including seeds) and placental tissue was 74 ± 6 g/100 g, 13 ± 2 g/100 g and 13 ± 4 g/100 g, based on our measurements. The differences in the physicochemical properties of different tomato tissues may affect their dielectric properties, which would result in different microwave heating rates. Thus, it is helpful to know their individual dielectric properties to develop microwave pasteurization and sterilization processes for specific tomato products.

It is known that many factors may influence the dielectric properties of a given food, including frequency, temperature, moisture content, salts and other food constituents (Tang, 2005). NaCl and $CaCl_2$ are the two salts most commonly added to canned tomato products; the former is for improved taste while the latter is a firming agent to retain texture. Several publications have discussed specific correlations between dielectric properties of foods and salt levels, frequency and food matrix (Ahmed, Ramaswamy, & Raghavan, 2007; Goedeken, Tong, & Virtanen, 1997; Guan, Cheng, Wang, & Tang, 2004; Wang et al., 2011; Zhang, Lyng, & Brunton, 2007). Little information is available on the influence of salts on the dielectric properties of tomatoes. Only one analysis conducted by Reyes et al. (2007) studied the dielectric spectroscopy of cherry tomatoes dehydrated with sucrose, NaCl and calcium lactate solutions at 2450 MHz. However, a very high salt concentration was used in Reyes's study (1–20 g/100 g of NaCl, and 1–2 g/100 g of calcium lactate) in order to create osmotic conditions for dehydration. In the current study, the effect of NaCl and $CaCl_2$ on the different tomato tissues was discussed for typical levels found in commercially canned tomato products.

The objectives of the current study were: (1) measuring the dielectric properties of the three different tomato tissues (pericarp, locular and placental tissues) in a temperature range of 22–120 °C, over 300–3000 MHz; (2) studying the effects of tomato compositions, temperature, frequency, NaCl and $CaCl_2$ addition on their dielectric properties, particularly at the microwave industrial frequencies of 915 and 2450 MHz; (3) investigating their loss mechanism; (4) determining the microwave penetration depths for the three tomato tissues.

2. Materials and methods

2.1. Sample preparation

Fresh Roma tomatoes were purchased from a local grocery store (Safeway, Pullman, WA, USA). After washing, tomatoes were quartered and the three tissues were separated: pericarp tissue (including skin), locular tissue (including seeds in the locular cavity) and placental tissue (Fig. 1). Each tissue was collected and blended into a homogenate individually. A total of 25 ml tomato sample made from 2–3 tomatoes was used for each measurement. Separate samples were prepared with 0.2 g/100 g of NaCl and 0.055 g/100 g $CaCl_2$ (equivalent to containing 200 mg/kg Calcium) to evaluate the effects of salt addition on their dielectric properties. The salt concentrations were chosen based on common practices in the tomato canning industry.

2.2. Moisture content, pH and total soluble solids

Physiochemical properties of the three tomato tissues including moisture content, pH and soluble solid content were analyzed immediately after samples were prepared as described above. Determination of moisture content was carried out in a vacuum oven following AOAC method 920.151 (AOAC, 2005). pH was measured using a Fisher Scientific Accumet pH meter. Total soluble solids were assessed by optical refractometer (Atago Co. LTD, Japan) and expressed as °Brix. All measurements were conducted in triplicates.

2.3. Determination of dielectric properties

The dielectric properties of tomato samples were measured using an open-ended coaxial probe connected to an HP 8752C network analyzer (Hewlett Packard Corp., Santa Clara, CA, USA) with system accuracy within 5% of error. An Agilent 85032B type N calibration kit which included open/short circuits and a 50 Ω load was used to calibrate the network analyzer. Then, the open-ended coaxial probe was calibrated by an Agilent 85070E dielectric probe kit, with air, short circuit, and deionized water (25 °C). After the calibration of the analyzer and the probe, tomato samples were added and tightly sealed in a test cell (Fig. 2). The test cell was designed to hold the sample against the probe while allowing the sample temperature to be raised by a fluid (circulated from an oil bath) in the jacket wall to the designated temperature (Wang, Wig, Tang, & Hallberg, 2003). To avoid air bubble formation which could influence the probe sensor reading and cause error of a measurement, tomato samples were vacuum degassed (KOCH Packaging Supplies Inc., Kansas City, MO) before each filling. Each measurement was repeated three times. The dielectric properties (ε' and ε'') were determined over a frequency range of 300–3000 MHz for temperatures ranging 22–120 °C in 20 °C increments. Statistical analysis was performed using Matlab 7.0 (The MathWorks, Inc., 2004), employing a Student's t-test ($\alpha = 0.05$).

2.4. Measurement of ionic conductivity

The dielectric loss mechanisms of biological materials in electromagnetic energy fields mainly include polar, electronic, atomic and Maxwell–Wagner responses (Metaxas & Meredith, 1983). At microwave frequency ranges (915 and 2450 MHz), the dominant loss mechanisms in high moisture foods, such as tomatoes, are water dipole dispersion and conductive (ionic) charge migration, and can be expressed as (Ryynänen, 1995):

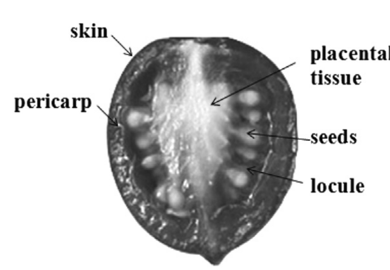

Fig. 1. Illustration of different anatomical structures of tomato fruits.

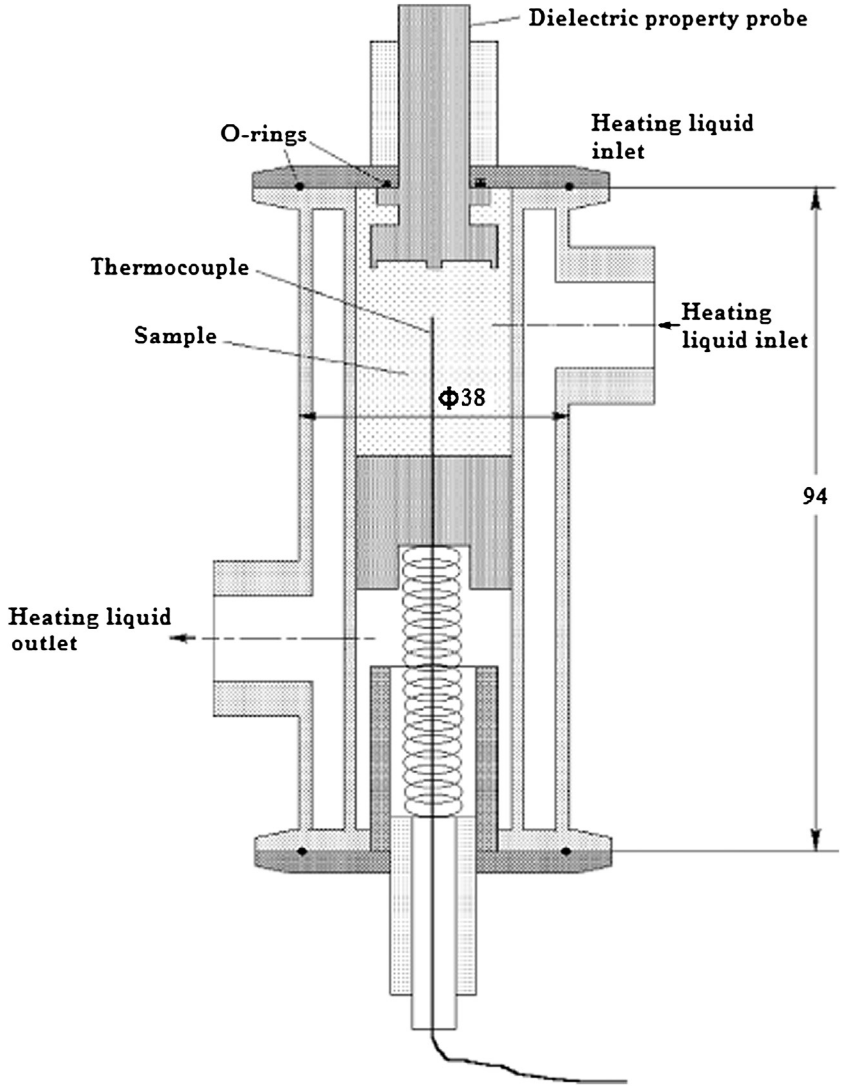

Fig. 2. Schematic diagram of pressure-proof test cells used for dielectric properties measurement (from Wang et al., 2003), dimensions are in mm.

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma \quad (1)$$

where ε''_d represents contributions of dipole dispersion to a material's dielectric loss factor and ε''_σ represents contributions of ionic conduction to dielectric loss factor. Since

$$\varepsilon''_\sigma = \frac{\sigma}{2\pi f \varepsilon_0} \quad (2)$$

We take logarithms of both sides of Eq. (2) to get

$$\log \varepsilon''_\sigma = -\log f + \log \frac{\sigma}{2\pi\varepsilon_0} \quad (3)$$

where ε_0 is the permittivity of free space or vacuum (8.854×10^{-12} F/m), σ is the ionic conductivity (S/m) of a given material, and f is frequency (Hz).

Ionic conductivity of pureed tomato tissues was measured at 22, 40, 60 and 80 °C, using an electrical conductivity meter (Cole-Parmer Con 500 conductivity meter, Chicago, IL) with a direct current of 500 mA. Thirty-five ml tomato homogenate was poured into a Corning tube (Corning Incorporated, NY) and the probe was placed in the center of the sample. The tube was sealed with Parafilm, and placed in a water bath (Thermo Electron Corporation, Waltham, MA, USA) to heat to the desired test temperature. A Type-T thermal couple (accuracy ± 0.5 °C) was inserted into the center of the sample to check the temperature. Experiments were done in triplicate.

2.5. Determination of power penetration depth

The penetration depth of microwaves is a measure of how deep microwave radiation can penetrate into a material. It is defined as the depth where the dissipated power is reduced to 1/e of the initial power entering the surface, and can be calculated by the following equation (Von Hippel, 1954)

Table 1
Moisture content, pH and soluble solids content of pericarp, locular and placental tissues in raw tomatoes.

	Moisture content, (g/100 g)	pH	Soluble solids, °Brix
Pericarp tissue	94.6 ± 0.4	4.15 ± 0.01	4.03 ± 0.06
Locular tissue	93.8 ± 0.5	4.41 ± 0.08	4.57 ± 0.06
Placental tissue	94.5 ± 0.4	4.19 ± 0.01	4.30 ± 0.14

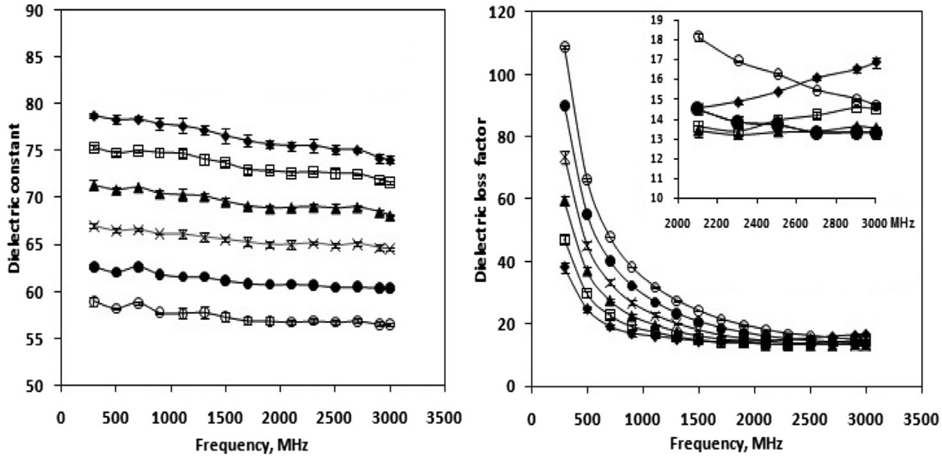

Fig. 3. Dielectric properties of raw tomato locular tissue as a function of temperature and frequency (◆ 22 °C; □ 40 °C; ▲ 60 °C; × 80 °C; ● 100 °C; ○ 120 °C). Data are the means ± S.D ($n = 3$).

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left(\sqrt{1+\left(\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right)}-1\right)}} \quad (4)$$

where d_p is the penetration depth (m) and c is the speed of light in free space (3×10^8 m/s).

Microwave power penetration depth is generally used to select appropriate thickness of food inside packages to ensure a relatively uniform heating along the depth of a food during dielectric heating processes (Wang et al., 2003; Wang, Tang, Rasco, Kong, & Wang,

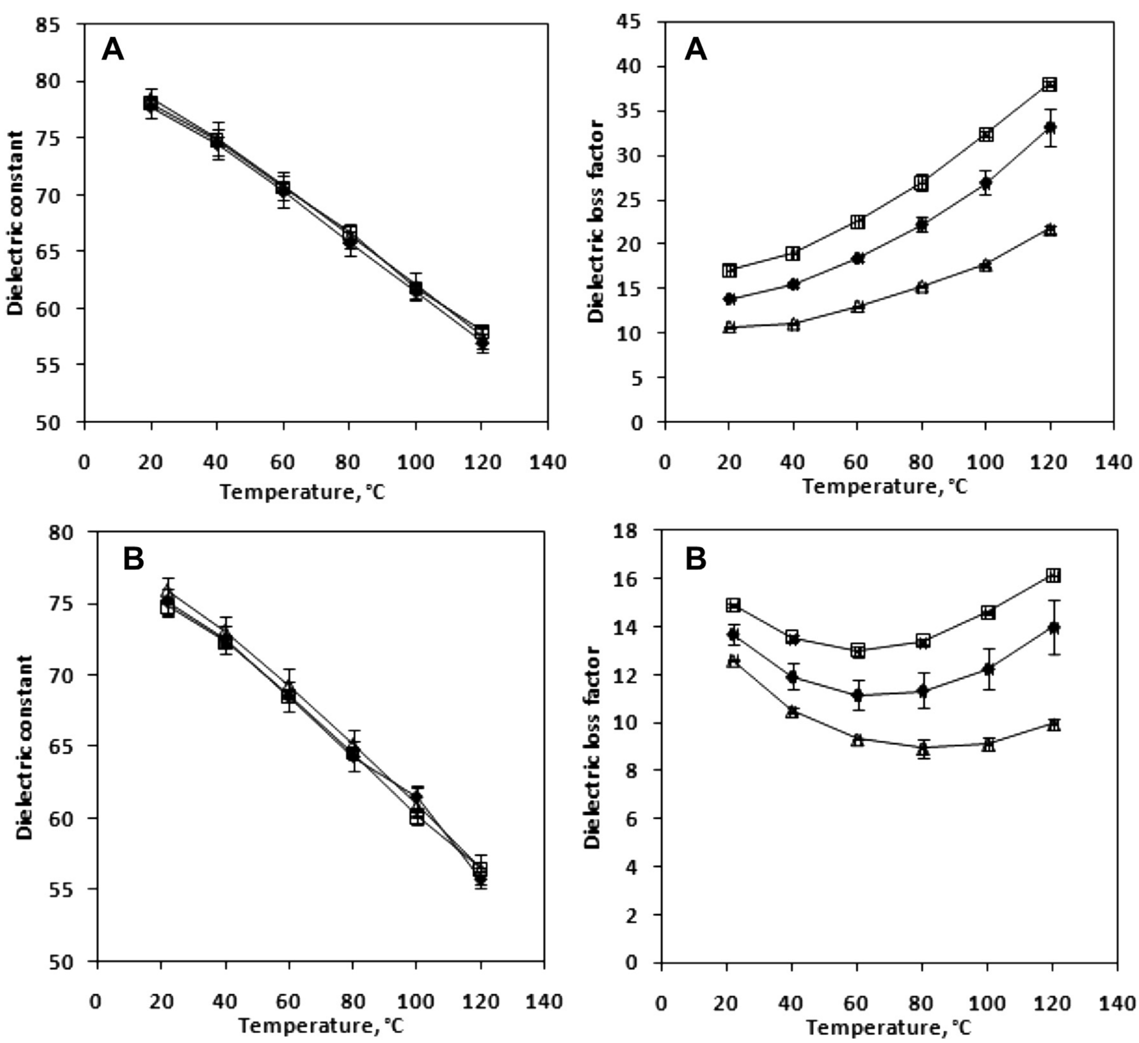

Fig. 4. Dielectric properties of raw pericarp (◆), locular (□) and placental (△) tissues at 915 (A) and 2450 (B) MHz. Data are the means ± S.D ($n = 3$).

2008). The penetration depth of microwaves into tomato samples was calculated at 915 and 2450 MHz, at temperatures of 22, 40, 60, 80, 100, and 120 °C.

3. Results and discussion

3.1. Physicochemical properties of pericarp, locular and placental tissues of raw tomatoes

The moisture content, pH and soluble solids content of the three tissues of raw tomato samples used in this study are reported in Table 1. The moisture content in the three tissues was very high and varied from 93–95 g/100 g. Both the pH and soluble solids content in the locular tissue were the highest among the three tissues, with a value of 4.41 and 4.57 °Brix, respectively. Moretti, Sargent, and Huber (1998) studied the chemical composition and physical properties in different tomato tissues and provided information about other components, including vitamin C, total carotenoids and chlorophyll. However, due to their large molecular weight and low content in the total sample, those components have little influence on the dielectric loss factor and thus were not analyzed in the current study. Since the moisture content in the three tomato tissues was similar and at a high value, one possible reason for the difference in their dielectric loss factors might be the different ionic conductivity due to the different amount and mobility of charged ions in the test tissues. This was confirmed by our measurement, in which we obtained an average ionic conductivity of 5.81, 7.42 and 5.01 mS/cm (1 mS/cm = 0.1 S/m) for pericarp, locular and placental tissues, respectively.

3.2. Dielectric properties of pericarp, locular and placental tissues of raw tomatoes

Fig. 3 shows typical trends for changes in dielectric constant and loss factor of tomato locular tissue over temperature and frequency. The dielectric constant decreased linearly with increasing temperature, about a 3–5 unit reduction for every 20 °C temperature increase at the same frequency. In general, the dielectric constant also decreased with increasing frequency. Unlike the dielectric constant, the effect of temperature on the loss factor behaved in an opposite manner, increasing with increasing temperature. The loss factor of tomatoes also decreased with increasing frequency, more sharply at lower frequencies (300–1500 MHz). At low temperatures (22 and 40 °C), a slight increase in loss factor was observed at the higher frequencies after the value decreased to the minimum at around 2000 MHz. These same trends noted for effects of temperature and frequency on dielectric properties of the locular tissues were also observed in tomato pericarp and placental tissues. These trends in tomato tissues are in agreement with those observed in other fresh fruits and vegetables with high moisture content (Feng

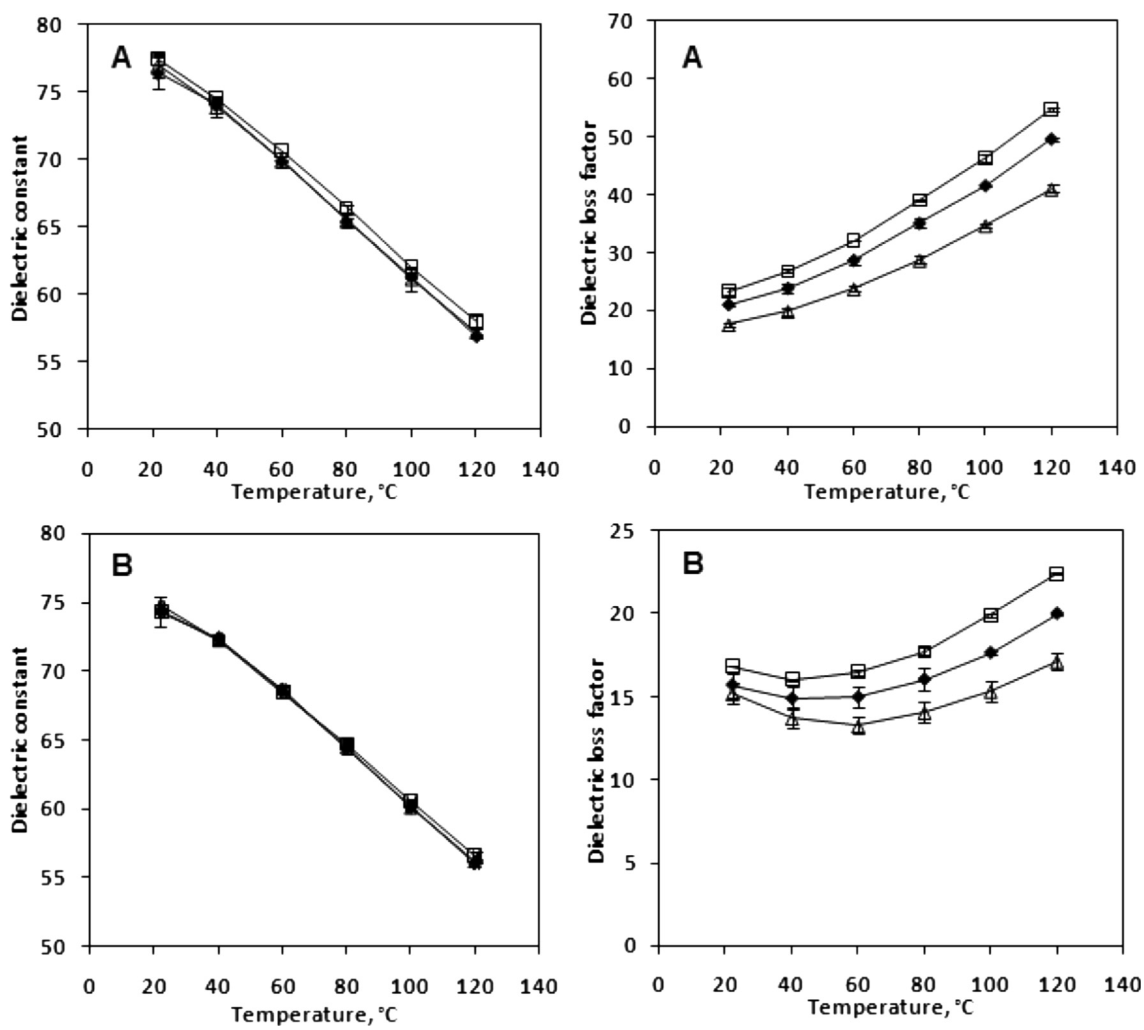

Fig. 5. Dielectric properties of tomato pericarp (◆), locular (□) and placental (△) tissues with 0.2 g/100 g of NaCl at 915 (A) and 2450 MHz (B). Data are the means ± S.D ($n = 3$).

Table 2
Dielectric properties of tomato pericarp, locular and placental tissues with 0.2 g/100 g of NaCl and 0.055 g/100 g of $CaCl_2$ at 915 and 2450 MHz.

Temp (°C)		915 MHz		2450 MHz	
		ε'	ε''	ε'	ε''
Pericarp tissue	22	77.9 ± 0.5	22.5 ± 0.2	76.0 ± 0.7	17.1 ± 0.1
	40	74.6 ± 0.9	26.3 ± 0.0	73.2 ± 0.9	16.1 ± 0.2
	60	70.6 ± 0.8	31.6 ± 0.6	69.4 ± 0.8	16.4 ± 0.2
	80	66.3 ± 0.7	38.5 ± 0.4	65.5 ± 0.6	18.0 ± 0.2
	100	61.7 ± 0.8	47.3 ± 0.3	60.9 ± 0.6	20.4 ± 0.1
	120	57.7 ± 0.7	55.9 ± 0.3	56.9 ± 0.9	23.1 ± 0.2
Locular tissue	22	77.7 ± 0.2	25.9 ± 0.4	75.1 ± 0.4	18.5 ± 0.2
	40	75.2 ± 0.3	30.4 ± 0.2	73.1 ± 0.1	18.0 ± 0.2
	60	71.2 ± 0.2	36.7 ± 0.3	69.7 ± 0.3	18.9 ± 0.3
	80	67.2 ± 0.5	44.6 ± 0.2	66.0 ± 0.6	20.5 ± 0.4
	100	63.0 ± 0.4	54.4 ± 1.0	61.6 ± 0.4	23.5 ± 0.5
	120	59.1 ± 0.4	63.3 ± 1.7	58.1 ± 0.2	26.2 ± 0.5
Placental tissue	22	76.5 ± 0.1	20.9 ± 0.2	74.3 ± 0.4	16.8 ± 0.1
	40	74.0 ± 0.4	24.2 ± 0.2	72.0 ± 0.2	15.7 ± 0.1
	60	69.9 ± 0.3	28.9 ± 0.3	68.5 ± 0.4	15.9 ± 0.3
	80	65.7 ± 0.0	34.8 ± 0.0	64.6 ± 0.1	16.7 ± 0.2
	100	61.3 ± 0.3	41.8 ± 0.5	60.3 ± 0.1	18.7 ± 0.1
	120	57.3 ± 0.7	49.3 ± 0.4	56.4 ± 0.4	20.7 ± 0.2

et al., 2002; Ikediala et al., 2000; Nelson et al., 1994; Seaman & Seals, 1991).

The dielectric properties of different tomato tissues at 915 and 2450 MHz are shown in Fig. 4. At 915 MHz, the three tomato tissues had the same dielectric constant at each temperature, with the value decreasing from around 78 at 22 °C to 57 at 120 °C. However, the dielectric loss factor of the three tomato tissues differed from each other at each temperature, from 10–17 at 22 °C to 21–38 at 120 °C. The placental tissue had the lowest dielectric loss factor while the locular tissue showed the highest value at each temperature. About a 3–5 unit increment of the loss factor of the three tomato tissues was observed at the same temperature, from placental tissue, locular tissue to pericarp tissue, accordingly. The same trends were observed in dielectric constant of the three tomato tissues at the frequency of 2450 MHz, with a slightly lower value at each temperature compared to those at 915 MHz. For the dielectric loss factor of the three tomato tissues at 2450 MHz, their values were still arranged in the same order, with the lowest being the placental tissue and the highest locular tissue. However, the changes in their dielectric loss factors at 2450 MHz were different. Raising the temperature at this frequency, the dielectric loss factor initially decreased then increased when temperature reached or exceeded 80 °C, exhibited a U-shapetrend. At higher temperatures, the differences among the three tomato tissues were more apparent. The differences in dielectric loss factor of tomatoes with temperature between the two frequencies (915 and 2450 MHz) might result from the differences in their dominant loss mechanism. At the lower frequencies, dielectric loss due to ionic conductivity is more important while at higher frequencies, dipolar rotation of free water is the dominant contributor (Calay, Newborough, Probert, & Calay, 1995; Ryynänen, 1995; Tang, 2005). The dielectric loss factor of tomatoes continued increasing with increasing temperatures at 915 MHz because conductive loss played the dominant role and it increased with temperature increase. But at 2450 MHz, dipolar loss became dominant, which decreased with

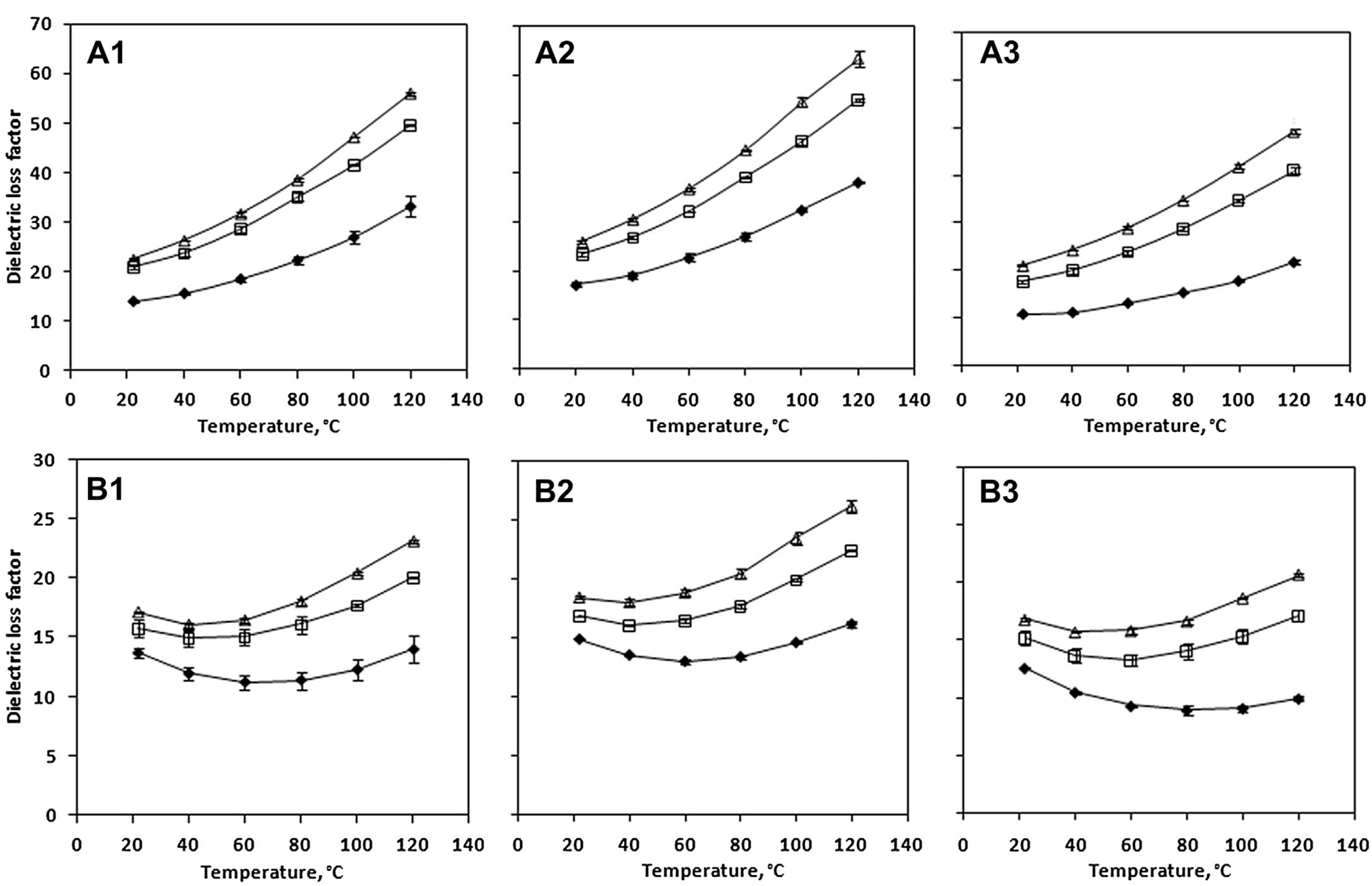

Fig. 6. Dielectric loss factor of tomato pericarp (A1 & B1), locular (A2 & B2) and placental (A3 & B3) tissues at 915 (A) and 2450 (B) MHz (◆ raw sample; □ added with 0.2 g/100g of NaCl; △ added with 0.2 g/100g of NaCl and 0.055 g/100g of $CaCl_2$). Data are the means ± S.D ($n = 3$).

temperature increase. Raising temperature initially decreased the overall dielectric loss factor in tomatoes due to the dominant dipolar loss, and then increased because conductive losses took over at higher temperatures.

3.3. Effect of NaCl

Values for the dielectric constants and loss factors of the three tomato tissues with addition of 0.2 g/100 g NaCl at 915 and 2450 MHz are summarized in Fig. 5. For the dielectric constant, the three tissues gave the same results as those without NaCl addition at each frequency, with higher values at 915 MHz than those at 2450 MHz. At each frequency, although the dielectric constant of the locular tissue was slightly higher than the other two tissues, no significant difference was found among these values of the three tomato tissues at each temperature. A significant difference was found in their corresponding dielectric loss factors. At 915 MHz, the dielectric loss factor was greatly increased compared to the samples without NaCl addition (Fig. 4), from 10–17 to 17–24 at 22 °C, and 21–38 to 41–55 at 120 °C. The increase in the loss factor of the three tomato tissues is more pronounced at high temperatures. The same changes in dielectric loss factor of the three tomato tissues with NaCl addition were observed at 2450 MHz frequency. These results indicate that 0.2 g/100 g NaCl didn't influence the dielectric constant of tomato samples, but apparently increased their dielectric loss factor. The increase of loss factor of the three tomato tissues may be explained by an increase of ionic conductivity due to dissolved ions coming from NaCl. This positive effect on the loss factor with increasing salt level was previously found in many foods, such as salmon fillets with 0–0.5 g/100 g NaCl (Wang et al., 2009), potato purees with 0–7 g/100 g NaCl (Guan et al., 2004; Wang et al., 2011), meat with 0–5 g/100 g salt (Lyng, Zhang, & Brunton, 2005; Tanaka, Mallikarjunan, Kim, & Hung, 2000; Zhang et al., 2007), surimi with 0–6 g/100 g NaCl (Yaghmaee & Durance, 2001), and butter with 0–0.6 g/100 g Na^+ (Ahmed et al., 2007). However, salting a product may also reduce the free water content due to the binding of free water molecules by the dissolved ions, therefore depressing the dielectric constant (Ahmed et al., 2007;Calay et al., 1995; Zhang et al., 2007). Since the NaCl concentration used in the current study was only 0.2 g/100 g, in such a high moisture-content food these binding effects on reducing the overall dielectric constant of the tomato tissue maybe negligible. A similar observation was made by Ikediala, Hansen, Tang, Drake, and Wang (2002), who showed that up to 2 g/100 g NaCl addition to saline water produced little change in its dielectric constant at 915 MHz.

3.4. Effect of $CaCl_2$

Calcium is often added as a firming agent to retain tomato texture. The effect of calcium on the dielectric properties of the three tomato tissues was investigated. According to the FDA regulation on calcium addition to canned tomato products (≤800 mg/kg calcium by weight in the finished product) and typical commercial processing practices, a concentration of 200 mg/kg calcium

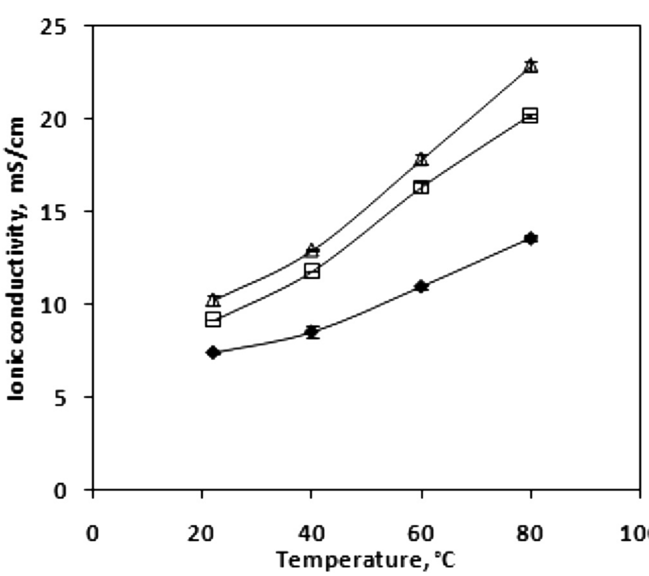

Fig. 7. Ionic conductivity of tomato locular tissue as a function of temperature (◆ raw sample; □ added with 0.2 g/100 g of NaCl; △ added with 0.2 g/100 g of NaCl and 0.055 g/100 g of $CaCl_2$). Data are the means ± S.D ($n = 3$).

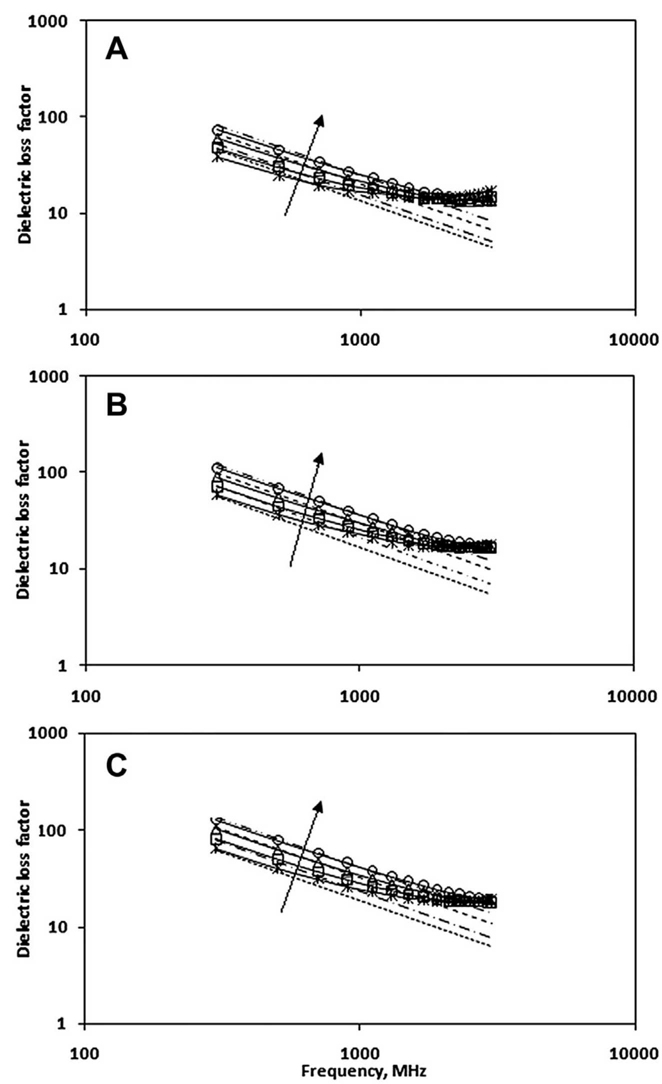

Fig. 8. Measured ε'' and calculated ε_σ'' of tomato locular tissue (A raw sample; B with NaCl; C with NaCl & $CaCl_2$) as a function of frequency and temperature (—✳— 22 °C, measured; —□— 40 °C, measured; —△— 60 °C, measured; —○— 80 °C, measured; ········ 22 °C, calculated; -·-·- 40 °C, calculated; ----- 60 °C, calculated; –·– 80 °C, calculated). Arrows show the influence of increasing temperature. Data are the means ± S.D ($n = 3$).

(equivalent to 0.055 g/100 g $CaCl_2$) was added to each tomato sample, along with the 0.2 g/100 g NaCl. Dielectric properties of tomato pericarp, locular and placental tissues with these two added salts are summarized in Table 2. Again, at a specific frequency (915 or 2450 MHz), no significant difference was found in the value of the measured dielectric constant for the three tomato tissues, while an apparent difference existed in their dielectric loss factor at each temperature. The dielectric loss factor of each tissue at the frequency of 915 MHz varied from 20–26 at 22 °C, to 50–64 at 120 °C. Similar to the situation with NaCl, addition of $CaCl_2$ only influenced the dielectric loss factor of tomato samples. Ikediala et al. (2002) also reported that increasing the concentration of $CaCl_2$ solution from 0.1 g/100 g to 2.0 g/100 g at the frequency of 915 MHz sharply increased its loss factor, but resulted in little change in its dielectric constant.

A better understanding of the effects of NaCl and $CaCl_2$ on the dielectric loss factor of different tomato tissues can be seen in Fig. 6. Although the changing trends of the dielectric loss factors of three tomato tissues with temperatures were different at the two frequencies (915 and 2450 MHz), the effects of either salt addition were the same. Both salts increased the dielectric loss factor. Fig. 6 also shows the increase in loss factor at high temperatures was more evident than at low temperatures. Besides, adding salts sharply increased the loss factor in tomatoes with higher temperatures at 2450 MHz, lowering the turning point of temperature where their loss factor started to increase with increasing temperature.

3.5. Effect of ionic conductivity on dielectric loss factor

As shown in Eqs. (1)–(3), two major dominant contributors to the value of dielectric loss in high moisture food materials at microwave frequencies are ionic loss which results from migration of ions, and dipole loss which results from water dipole dispersion. The ionic conductivity is a function of the concentration and type of ions present, and the temperature. Generally, the ionic conductivity of a very dilute aqueous solution is proportional to the amount of dissolved ions it contains (Gray, 2004). For high moisture foods, ionic conductivity normally increased with higher temperatures due to reduced viscosity and increased mobility of the ions (Tang, Feng, & Lau, 2002). The values of ionic conductivity of tomato locular tissue at 22, 40, 60 and 80 °C are shown in Fig. 7. A sharp increase in measured ionic conductivity was observed after the addition of salt (NaCl or $CaCl_2$), and the increase was more pronounced at high temperatures.

The dielectric loss factor value of tomato locular tissue contributed by ionic conduction (ε_σ'') was calculated according to Eq. (3) and shown in Fig. 8, along with the corresponding overall dielectric loss factor values (ε'') measured by the network analyzer. The loss factors of tomato locular tissue with or without salt had similar trends. There is a good agreement between measured ε'' and calculated ε_σ'' values at all temperatures in the frequency range below 700 MHz. This phenomenon demonstrated that the dielectric loss factor of tomato locular tissue was governed mainly by ionic conduction in the lower end of the studied frequency range. The increase in the dielectric loss factor with increasing temperature was indeed caused by the increase in ionic conductivity (Fig. 7). When the frequency increased above 700 MHz, the measured ε'' values started to shift above the calculated ε_σ'' values. The deviation was caused by water dipole dispersion which took place in the tomato samples at the high frequency range. The results are also in agreement with Fig. 6, which indicates that the increase in measured ε'' of each tissue was not proportional to the increase of total molar concentration of ions from added salts. The contribution of dipole rotation to the overall dielectric loss factor became more important when moving toward higher frequencies. The peak value of ε'' due to dipole water at room temperature with respect to frequency occurs between 16 and 20 GHz (Mashimo, Kuwabar, & Higasi, 1987; Tang et al., 2002). Raising temperature would move this peak toward higher frequency bands. Fig. 8 shows that the dipole loss had a larger influence at low temperatures. At high temperatures ionic conductivity increases and contributes more to the overall loss factor. These results agree with our previous results of ε'' (tomatoes) vs. temperature profiles (Figs. 4–6), which were linear at 915 MHz while a U-shaped curve existed at 2450 MHz.

Table 3
Microwave penetration depth into tomato pericarp, locular and placental tissues at 915 MHz.

	Temp (°C)	Penetration depth (mm)					
		915 MHz			2450 MHz		
		Fresh	With 0.2 g/100 g NaCl	With 0.2 g/100 g NaCl & 0.055 g/100 g $CaCl_2$	Fresh	With 0.2 g/100 g NaCl	With 0.2 g/100 g NaCl & 0.055 g/100 g $CaCl_2$
Pericarp tissue	22	33.1 ± 0.3	22.0 ± 0.5	20.7 ± 0.1	12.4 ± 0.3	11.0 ± 0.2	10.0 ± 0.2
	40	29.1 ± 0.3	19.2 ± 0.7	17.4 ± 0.1	14.0 ± 0.5	11.5 ± 0.2	10.5 ± 0.2
	60	23.9 ± 0.3	15.6 ± 0.4	14.2 ± 0.2	14.5 ± 0.7	11.1 ± 0.1	10.0 ± 0.0
	80	19.3 ± 0.6	12.4 ± 0.3	11.5 ± 0.1	13.9 ± 0.8	10.1 ± 0.0	8.8 ± 0.1
	100	15.6 ± 0.7	10.3 ± 0.0	9.2 ± 0.1	12.6 ± 0.8	8.7 ± 0.1	7.6 ± 0.1
	120	12.4 ± 0.8	8.6 ± 0.1	7.8 ± 0.1	10.5 ± 0.8	7.4 ± 0.0	6.5 ± 0.0
Locular tissue	22	27.1 ± 0.9	19.9 ± 0.5	18.0 ± 0.3	11.4 ± 0.1	10.0 ± 0.0	9.2 ± 0.1
	40	24.0 ± 1.0	17.1 ± 0.2	15.2 ± 0.1	12.3 ± 0.1	10.4 ± 0.0	9.3 ± 0.1
	60	19.6 ± 0.7	14.0 ± 0.0	12.4 ± 0.1	12.5 ± 0.2	9.9 ± 0.1	8.7 ± 0.1
	80	16.1 ± 0.6	11.3 ± 0.0	10.1 ± 0.1	11.8 ± 0.1	8.9 ± 0.1	7.8 ± 0.1
	100	13.1 ± 0.1	9.4 ± 0.1	8.2 ± 0.1	10.4 ± 0.1	7.7 ± 0.1	6.6 ± 0.2
	120	11.0 ± 0.1	7.9 ± 0.0	7.0 ± 0.1	9.2 ± 0.1	6.7 ± 0.0	5.8 ± 0.2
Placental tissue	22	43.3 ± 0.4	26.2 ± 0.7	22.0 ± 0.2	13.5 ± 0.1	11.2 ± 0.5	10.1 ± 0.1
	40	41.0 ± 0.1	22.7 ± 0.8	18.8 ± 0.1	15.9 ± 0.1	12.1 ± 0.6	10.6 ± 0.1
	60	33.9 ± 0.5	18.6 ± 0.4	15.4 ± 0.1	17.4 ± 0.1	12.2 ± 0.5	10.2 ± 0.2
	80	28.1 ± 0.0	15.0 ± 0.4	12.6 ± 0.0	17.6 ± 0.7	11.2 ± 0.6	9.5 ± 0.1
	100	23.4 ± 0.4	12.2 ± 0.2	10.3 ± 0.1	16.7 ± 0.4	9.9 ± 0.4	8.2 ± 0.0
	120	18.6 ± 0.5	10.2 ± 0.2	8.6 ± 0.0	14.8 ± 0.2	8.6 ± 0.3	7.2 ± 0.1

3.6. Penetration depth

The penetration depth of microwaves in the three tomato tissues (pericarp, locular, and placental tissue) at the two microwave frequencies is summarized in Table 3. Fresh samples had the highest penetration depths, while the samples with the two salts added had the lowest values under the conditions studied. All of the three tomato tissues showed higher penetration depth at 915 MHz than their corresponding values at 2450 MHz, with average values varying from 7.0 to 43.3 mm for the former and 5.8–17.6 mm for the latter. Although the penetration depth of the three tomato tissues varied from each other, they exhibited very similar trends in their changes with salt addition, decreasing with increasing salt. For temperature changes, increasing temperature decreased their penetration depth at 915 MHz; while initially increased then decreased their penetration depth at 2450 MHz. For every 20 °C temperature increment at 915 MHz, the penetration depth decreased around 2–4 mm under the same condition; while the penetration depth changed around 0.2–2 mm at 2450 MHz. The tendency of change in penetration depth with increasing temperature is opposite to those in their loss factor, which is easy to understand because according to Eq. (4) ε'' is inversely related to d_p. The changes in ε'' affected d_p more than the influence from ε' in tomato samples used in our studies. A similar change in the penetration depth with temperature at 915 MHz has been reported for whey protein gel, macaroni and cheese by Wang et al. (2003), and pink salmon fillets by Wang et al. (2009).

4. Conclusions

Our results showed that dielectric loss factor of three tomato tissues (the pericarp, the locular and the placental tissues) were significantly different from each other, either with or without salt. But no significant differences were found in their corresponding dielectric constant. Salt addition at the typical commercial canned tomato product level (0.2 g/100 g NaCl or 0.055 g/100 g $CaCl_2$) sharply increased the loss factor of the three tomato tissues, but didn't affect their dielectric constant at the microwave frequencies (915 and 2450 MHz). Similar trends for changes in dielectric loss factor were observed in the three tomato tissues, decreasing with increased frequency, and increasing with salt addition. For the effects of temperature, increasing temperature continued increasing their dielectric loss factor at 915 MHz while initially increased then decreased their corresponding values at 2450 MHz, resulting from their different dominant loss mechanism at the two frequencies. Furthermore, a positive correlation was found between the loss factor of the tomato tissue and their ionic conductivity. At a specific frequency (either 915 or 2450 MHz), the penetration depth of the three tomato tissues varied from each other, but again exhibited similar change tendency. Results obtained in this study may be used for developing microwave pasteurization and sterilization processes for different tomato products, and also add new information to the database for computer simulation.

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