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REASEARCH ARTICLE

Pest control by microwave and radio frequency energy: dielectric properties of stone fruit

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Abstract Current pesticides such as methyl bromide are progressively removed from the market due to harmful residues in food. The stone fruit industries are thus seeking alternatives for postharvest control of insect pests. Microwave and radio frequency methods hold potential for postharvest thermal disinfestations of stone fruits to replace chemical fumigation. Knowledge of dielectric properties is essential for understanding the interaction between the electromagnetic fields and the target stone fruits and designing treatment beds in industrial applications. Here, we determined the dielectric properties of nectarine, peach, and plum between 10 and 1,800 MHz over a temperature range of 20–60 °C using an impedance analyzer. Our results show that the dielectric constant generally varied between 60 and 75, accounting for changes of 8–10 % due to temperature effect. But, the loss factor decreased linearly with frequency on the log scale at all temperatures for three stone fruits. The loss factor of Mediterranean fruit fly, nectarine, peach, and plum increased about 106, 108, 110, and 64 %, respectively, when the sample temperature increased from 20 to 60 °C. The penetration depth in all stone fruits decreased with increasing frequency and temperature. The loss factor ratio at 27 MHz of Mediterranean fruit fly to nectarine, peach, and plum was 1.65, 1.66, and 1.87 at 20 °C, respectively, suggesting potential differential heating between insects and host stone fruits in radio frequency treatments.

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1 Introduction

The value of the US stone fruit industry, such as nectarine, peach, and plum, reached 225,200, 1,071,790, and 160,000 tons in 2011 with a value of about US$129, 615, and 78 million, respectively (USDA-NASS 2012). Stone fruit are routinely fumigated with methyl bromide to control quarantine pests prior to export to Japan, Mexico, and Canada. Growers of stone fruits face major challenges in shipping their products when production areas are perceived to be infested by insect pests, such as the Mediterranean fruit fly (*Ceratitis capitata*). Many growers in California have faced economic hardship from introductions of exotic fruit fly species because of an inability to market their products whenever the growing area is under quarantine. Because of environmental pollutions, heath concerns, and regulatory actions, the chemical fumigation is proposed to be replaced by microwave (El-Naggar and Mikhaiel 2011; Singh et al. 2012; Ben-Lalli et al. 2013; Purohit et al. 2013) and radio frequency treatments (Wang et al. 2006, 2007; Tiwari et al. 2008; Jiao et al. 2012; AlFaifi et al. 2013). Especially for radio frequency heating, industrial applications have been conducted for disinfesting in-shell walnuts (Fig. 1). There is a need to determine dielectric properties of stone fruits for understanding the interaction between the electromagnetic fields and the target stone fruits.

Radio frequency refers to electromagnetic waves from 3 kHz to 300 MHz and microwave ranges from 300 MHz to 300 GHz (Komarov et al. 2005). Because of the congested bands of electromagnetic wave being used for communication purposes, the US Federal Communication Commission (FCC) has allocated several specific frequencies for industrial, medical, and scientific applications, including 13.56, 27.12, and

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Fig. 1 Photo of infested walnut (*inset*, *top left*) of an industrial-scale radio frequency system (Wang et al. 2007) and an infrared thermal (IR) image of walnut surface temperatures in a plastic container after radio frequency treatment (*inset*, *bottom left*)

40.68 MHz for radio frequency and 915 and 2,450 MHz for microwave (Komarov et al. 2005). During radio frequency and microwave heating, most agricultural products can store and absorb electromagnetic energy. Dielectric properties are the most important data for predicting dielectric heating rate and uniformity and guiding the treatment protocol design (Sosa-Morales et al. 2010) and are generally described in terms of the complex relative permittivity, ε:

$$\varepsilon = \varepsilon' - j\,\varepsilon'' = \tag{1}$$

where $j = \sqrt{-1}$. The relative dielectric constant, ε', is a measurement of a fruit to store energy, and the relative dielectric loss factor, ε'', measures the energy that is dissipated in the fruit from applied electric fields.

For rapid and volumetric heating using microwave and radio frequency energy, the temperature rise in a fruit due to absorption of electromagnetic energy and negligible heat loss can be described as follows (Nelson 1996; Wang et al. 2003a):

$$\rho C_{\mathrm{p}} \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11}\ f E^2 \varepsilon'' \tag{2}$$

where ρ is the density of the fruit in kilograms per cubic meter, C_{p} is the specific heat of the fruit in joules per kilogram. ΔT is the temperature rise in the fruit in degrees Celsius, Δt is the time duration in seconds, f is the frequency in hertz, and E is the electric field intensity in volts per meter. The heating rate is proportional to the dielectric loss factor of the fruit in addition to the frequency and electric field intensity.

Dielectric properties are essential for better understanding the heating behavior of the treated fruits in radio frequency or microwave systems and improving heating uniformity in fruits using computer simulation. Dielectric properties data have been reported in similar fresh fruits, including apples, cherries, grapes, mangoes, pineapples, tomatoes, and other fruits (Feng et al. 2002; Nelson 2003; 2005; Sipaghioglu and Barringer 2003; Wang et al. 2003b; 2005; Sosa-Morales et al. 2009; Zhu et al. 2012; Barba and Lamberti 2013; Peng et al. 2013; Solyom et al. 2013; Wang et al. 2013b). These data are largely influenced by frequency and temperature (Sosa-Morales et al. 2010; Zhu et al. 2012). Dielectric properties are also reported for many important insect pests, including potato beetle (Colpitts et al. 1992); woodworm (Andreuccetti et al. 1994); codling moth, Indian meal moth, navel orange worm, or Mexican fruit fly (Wang et al. 2003b); Mediterranean fruit fly (Wang et al. 2005); chestnut weevil (Guo et al. 2011); and cowpea weevil (Jiao et al. 2011). These data are compared with those of host products to predict the potential selective heating, which could be an advantage for microwave and radio frequency disinfestations (Nelson and Payne 1982; Wang et al. 2003a, 2013a; Shrestha and Baik 2013). The most promising frequency for selective heating of insects in dried food appears to be between 10 and 100 MHz (Nelson and Charity 1972; Wang et al. 2003a). Nelson and Stetson (1974) achieved a complete insect mortality of rice weevil in infested wheat at a low energy level at 39 MHz but unlikely at 2.45 GHz. In recent years, Wang et al. (2003a; 2013a) developed theoretical and experimental models for controlling codling moth and navel orange worm larvae by preferential heating in dry nuts at 27.12 MHz. Up to now, information is not available in the literature on dielectric properties of stone fruit for developing postharvest insect control treatments using radio frequency and microwave energy.

The objectives of this study were (1) to measure the dielectric properties of the stone fruits (nectarine, peach, and plum) as influenced by frequency (10–1,800 MHz) and temperature (20–60 °C) and then compare with published dielectric properties of the major targeted insect in the stone fruit, (2) to determine the temperature effect on the dielectric properties at interesting frequencies, and (3) to calculate the penetration depth of electromagnetic energy into these three fruits at frequencies of 27.12, 915, and 1,800 MHz related to industrial radio frequency and microwave heating applications as a function of temperature.

2 Materials and methods

2.1 Materials and sample preparation

Fresh nectarine (*Prunus persica* var. *nectarine*), peach (*Prunus persica*), and plum (*Prunus domestica*) samples were purchased from a local grocery store in Pullman, WA, USA.

The stone fruit samples were stored at 4 °C before measurement and kept at 20 °C room conditions overnight for equilibrium prior to experiments. The stone fruit was peeled, and the pulp was blended to obtain one puree sample. Because of the thin peel, the dielectric properties of stone fruit pulp could be representative of whole stone fruits as reported for similar fresh fruits, such as apples, cherries, and mangoes (Wang et al. 2003b; Sosa-Morales et al. 2009). The original moisture content of nectarine, peach, and plum was 87.6, 87.2, and 85.1 % wet basis (w.b.), respectively, which was determined by oven methods according to the AOAC standards (AOAC 2002).

Before recording dielectric property measurements, live Mediterranean fruit fly larvae were extracted from an artificial diet and were blended into slurry. The initial moisture content of the insect slurry was about 74 % w.b. About 30 cm^3 of slurry was used for each sample to avoid electromagnetic field perturbation by the sample holder. Tests with insect larvae were conducted immediately after blending to minimize degradation of the hemolymph and other constituents. The dielectric properties data of Mediterranean fruit fly larvae at 10–1,800 MHz and 20–60 °C were obtained from Wang et al. (2005).

2.2 Measurement of dielectric properties

Dielectric properties of nectarine, peach, and plum samples were measured at 20, 30, 40, 50, and 60 °C, which cover the temperature range suitable for thermal disinfestations of agricultural products. The dielectric properties data were obtained with an impedance analyzer (Model 4291B, Agilent Technologies, Inc., Palo Alto, CA) over a frequency range from 10 to 1,800 MHz (Fig. 2). A temperature-controlled stainless steel cylindrical sample holder (20 mm in inner diameter and 94 mm in height) was built for use with an open-ended coaxial-line probe to keep the sample at the given moisture content during the measurement. A constant temperature water bath (Model 1157, VWR Scientific Products, Niles, IL, USA) was used to control the sample temperature by circulating the water (15 l/min) into the jacket of the sample holder. A type-T thermocouple (TMQSS-020U-6, Omega Engineering, Inc., Stamford, CT, USA) with 0.8 s response time was used to monitor the sample center temperature inside the holder. The dielectric constant (ε')and loss factor (ε'') were calculated with the Dielectric Probe Kit software, which provided values of these two parameters from the reflection coefficient of the material in contact with the active tip of the probe. The dielectric properties measurements were conducted at 201 discrete frequencies on a logarithmic scale. Detailed information about the system and procedure can be found in Wang et al. (2003b).

2.3 Procedures

Prior to the measurement, the impedance analyzer and the computer attached to the analyzer were turned on and kept in a standby condition for at least 1 h before calibration. Using a standard, Agilent 4291B calibration kit, the impedance analyzer was calibrated with an open, a short, a low-loss capacitance, and a 50-Ω load in sequence. The open-ended coaxial-line probe was then attached to the system and further calibrated with air, the short, and deionized water (electrical conductivity <1.0 mS/cm) at 25 °C. A personal computer and software (85070D, Agilent Technologies, Inc., Santa Clara, CA, USA) were used to record and calculate the measured data. To minimize errors, the impedance analyzer, electric cable, and probe were maintained at fixed positions during calibration and measurement.

Prior to and after each measurement, the probe and the sample holder were cleaned with deionized water and dried with dry air. The sample confined within the sample holder was compressed with a spring at the base to ensure a close contact between the probe tip and the sample during measurements. The sample temperature was raised incrementally to five different levels. About 15 min was needed for the sample

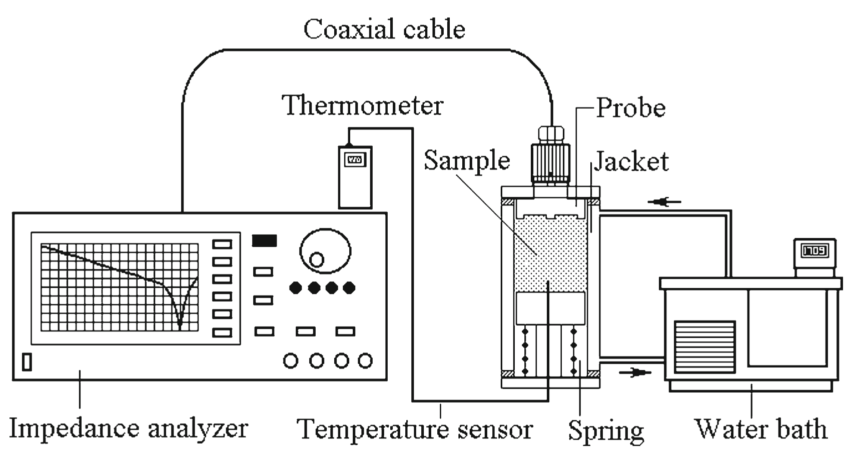

Fig. 2 Schematic view of a dielectric properties measurement system (Wang et al. 2003b)

temperature to increase from one to the next temperature level. Mean values and standard deviations (SD) of dielectric properties data were calculated from two replicates.

2.4 Penetration depth

Penetration depth is an important parameter in evaluating heating uniformity and designing the treatment sample thickness during microwave and radio frequency heating. The equation used to determine microwave and radio frequency power penetration depth in a material is defined as (von Hippel 1954).

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}} \quad (3)$$

where d_p is the penetration depth in m and c is the speed of light in free space (3×10^8 m/s). After the dielectric properties were obtained, the penetration depth was estimated for the three stone fruit samples at the three selected frequencies and five temperatures.

3 Results and discussions

3.1 Frequency-dependent dielectric properties

Figure 3 shows the frequency-dependent dielectric constant (ε') and loss factor (ε'') of nectarine, peach, and plum at five temperatures. The dielectric properties of the three stone fruits demonstrated similar trends: they decreased with increasing frequency. However, the dielectric constant almost kept

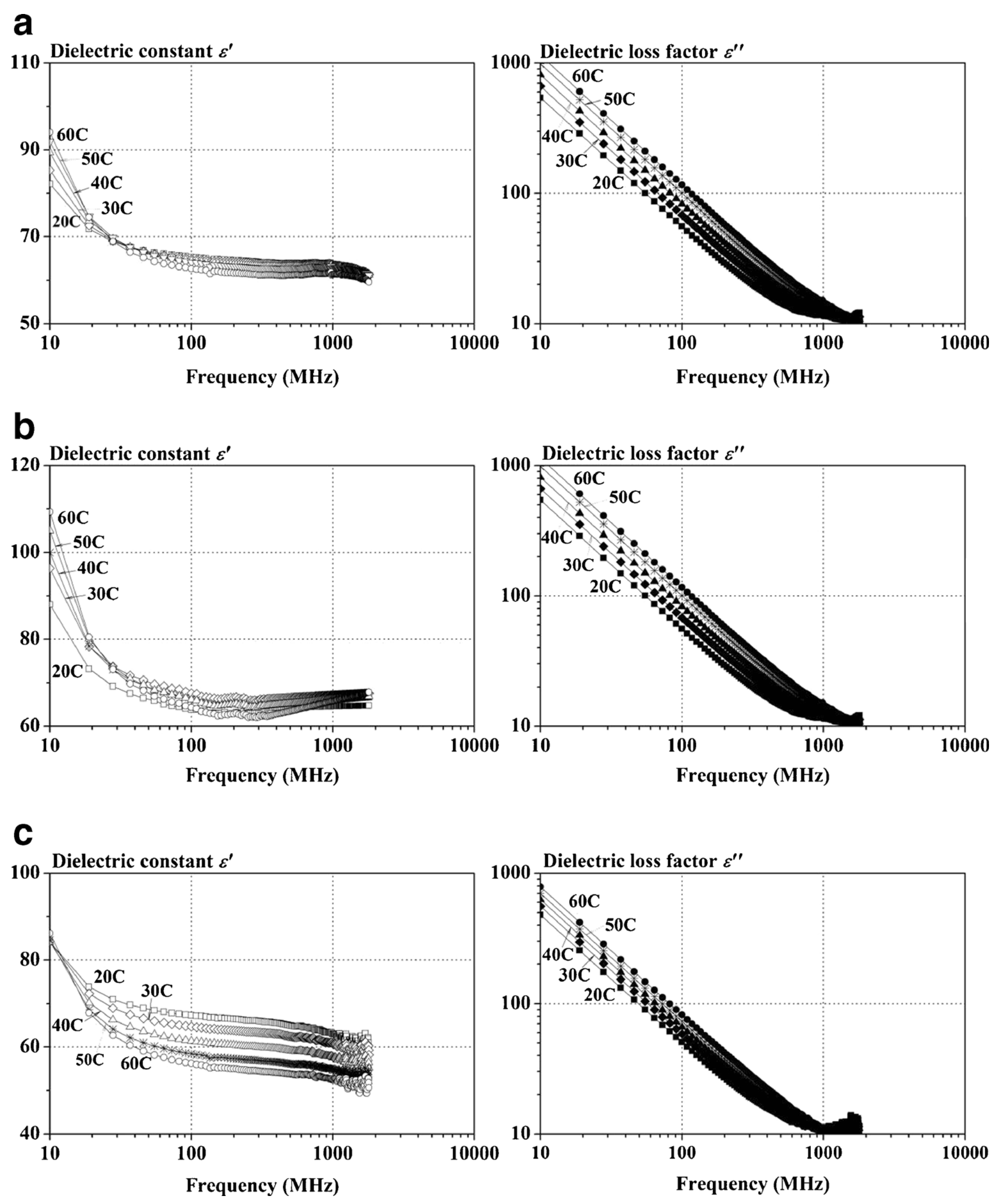

Fig. 3 Frequency-dependent dielectric constant (ε') and loss factor (ε'') of nectarine (**a**), peach (**b**), and plum (**c**) at five temperatures

constant after frequencies higher than 100 MHz. The loss factor decreased linearly with frequency on the log scale at all temperatures, especially below 300 MHz, which could be caused by dominant effects of ionic conduction (Liu et al. 2009; Gao et al. 2012) and was common in high-moisture fruits (Sosa-Morales et al. 2009; Zhu et al. 2012). For example, the slopes and coefficient of determination R^2 of log ε'' vs. log f below 300 MHz were estimated to be −0.97 and 0.99, −0.96 and 0.99, and −0.95 and 0.99 for nectarine, peach, and plum, respectively, at 20 °C. The slope of close to −1 suggested that the effect of dipole rotation on RF heating was negligible (Guo et al., 2010). The loss factor increased with increasing temperature, but the temperature effect on the dielectric constant was negligible due to small changes of 8–10 % at the selected frequencies. The absolute value of the dielectric properties of nectarine and peach was in the same magnitude but higher than that of plum, which could be caused by its low moisture content (Zhu et al. 2012; AlFaifi et al. 2013).

3.2 Temperature-dependent dielectric properties

Figure 4 shows temperature-dependent dielectric properties of nectarine, peach, and plum for comparison at three given frequencies. The dielectric constant at 27 MHz was larger than those at 915 and 1,800 MHz. The dielectric constant decreased with increasing temperature only for nectarine and plum but first increased and then decreased for peach. Generally, the average value of the dielectric constant was around 50 to 75 for all tested temperatures and the selected

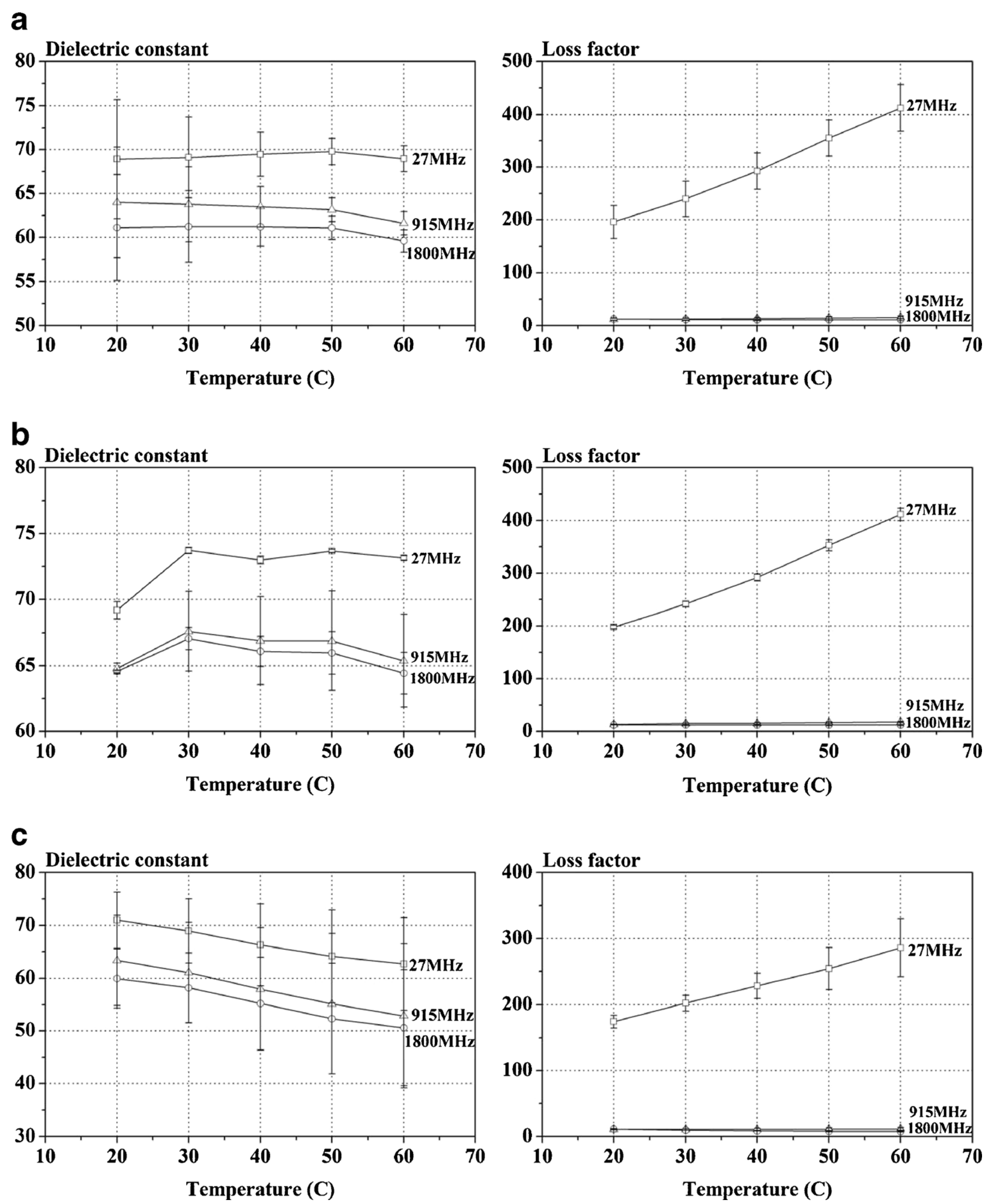

Fig. 4 Temperature-dependent dielectric properties of nectarine (**a**), peach (**b**), and plum (**c**) for comparison at three frequencies

Table 1 Calculated penetration depths of electromagnetic waves in three stone fruits at three frequencies and five temperatures

Fruit	Frequency (MHz)	Penetration depth (cm)				
		Temperature (°C)				
		20	30	40	50	60
Nectarine	27.12	10.6±0.9	9.3±0.8	8.2±0.6	7.3±0.4	6.7±0.4
	915	3.7±0.5	3.5±0.4	3.3±0.5	3.0±0.4	2.7±0.4
	1,800	1.7±0.2	1.9±0.2	1.9±0.3	2.0±0.3	1.9±0.3
Peach	27.12	10.5±0.1	9.3±0.1	8.3±0.1	7.4±0.1	6.7±0.1
	915	3.2±0.2	3.0±0.2	2.8±0.2	2.6±0.2	2.4±0.1
	1,800	1.8±0.1	1.8±0.1	1.9±0.1	1.9±0.1	1.8±0.1
Plum	27.12	11.5±0.3	10.4±0.3	9.5±0.4	8.9±0.5	8.3±0.7
	915	3.8±0.1	3.8±0.1	3.7±0.1	3.6±0.1	3.3±0.1
	1,800	1.8±0.1	2.1±0.1	2.3±0.1	2.4±0.1	2.5±0.1

frequencies. The loss factor of the three stone fruits increased with increasing temperature at each tested frequency, especially at 27 MHz. The loss factor of nectarine and peach was larger than that of plum, as found in Fig. 3. The increasing trend of loss factor with temperature at 27 MHz would result in accelerating heating in radio frequency heating systems, indicating that hot spots could become hotter due to increased absorption of radio frequency energy. These phenomena are also reported in Wang et al. (2005, 2013b), Guo et al. (2011), and Alfaifi et al. (2013).

3.3 Penetration depth

Penetration depth calculated from the measured dielectric properties of the three stone fruits is listed in Table 1 for three given frequencies and five temperatures. The penetration depth of all of the stone fruits decreased with increasing frequency and temperature. The penetration depth in nectarine and peach was similar but slightly lower than that in plum. The penetration depth in the radio frequency region was larger than that in the microwave range. Generally, the penetration depth in fresh fruits is very limited due to higher moisture contents (Nelson 2005; Wang et al. 2005; Sosa-Morales et al. 2009; Guo et al. 2007) and is much smaller than that in the dried fruits (Feng et al. 2002; Alfaifi et al. 2013), beans (Guo et al. 2010; Jiao et al. 2011), and nuts (Wang et al. 2003b, 2013b; Gao et al. 2012). The limited penetration depth would influence the treatment throughput and heating uniformity in multilayer samples.

3.4 Comparing dielectric properties of stone fruits with insects

The loss factor of Mediterranean fruit fly larvae followed a trend similar to that of stone fruits as influenced by frequency (Fig. 5). The loss factor of insects was clearly larger than that of stone fruits at 20 °C, especially in the radio frequency range (i.e., <300 MHz). The loss factor at 27 MHz increased with increasing temperature for insects and all stone fruits (Fig. 6). The relative increase of the loss factor reached about 106, 108,

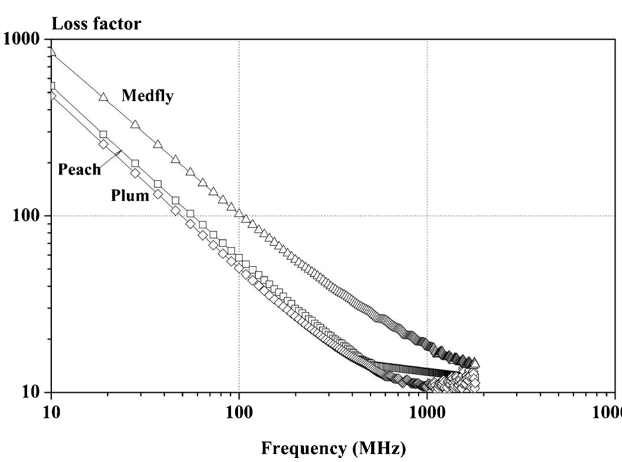

Fig. 5 Dielectric loss factor of peach and plum, as compared to the data of Mediterranean fruit fly (Wang et al. 2003b), as a function of frequency at 20 °C

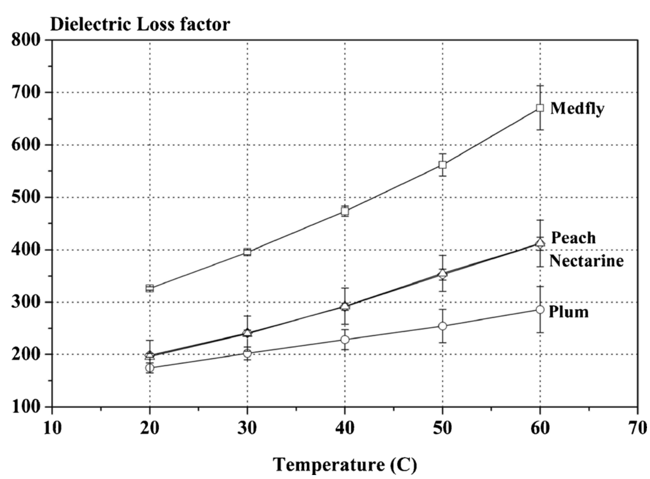

Fig. 6 Dielectric loss factor of nectarine, peach, and plum, as compared to the data of Mediterranean fruit fly (Wang et al. 2003b), as a function of temperature at 27.12 MHz

110, and 64 % for Mediterranean fruit fly, nectarine, peach, and plum, respectively, when the sample temperature increased from 20 to 60 °C. The loss factor ratio at 27 MHz of Mediterranean fruit fly to nectarine, peach, and plum was 1.65, 1.66, and 1.87 at 20 °C, and 1.62, 1.63, and 2.34 at 60 °C, respectively, suggesting the potentially differential heating. This loss factor ratio (1.63–2.34 in this study) at 27 MHz and 20 °C is smaller than that between chestnut weevil and chestnut (4, Guo et al., 2011), between Indian meal moth and raisin (26, Alfaifi et al. 2013), between cowpea weevil and black-eyed pea (100, Jiao et al. 2011), between naval orange worm and almond (184, Wang et al. 2013a), and between codling moth and walnut (397, Wang et al. 2003a). Although the final temperature difference in Eq. (2) between insect and host material depends not only on the loss factor ratio but also on the electric field intensity and thermal properties of these materials, this dielectric properties information is helpful to determine the potentially differential heating for practical radio frequency treatments.

4 Conclusions

Dielectric properties of nectarine, peach, and plum were measured by an impedance analyzer at different frequencies (10–1,800 MHz) and temperatures (20–60 °C). The dielectric loss factor decreased with increasing frequency but increased with increasing temperature, especially in radio frequency ranges. The penetration depth in all stone fruits decreased with increasing frequency and temperature. Differential heating for postharvest insect control might be possible since the loss factor of the targeted insect was 1.65–1.87 times that of stone fruits at 27 MHz and 20 °C and the loss factor ratio increased with increasing temperature. It could be applied to develop treatments that allow insect pests to be heated to a higher and lethal temperature while maintaining the product at lower temperature for good quality.

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