biosystems engineering 103 (2009) 297–303

Available at www.sciencedirect.com

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Research Paper: PH—Postharvest Technology

Dielectric heating as a potential post-harvest treatment of disinfesting mangoes, Part I: Relation between dielectric properties and ripening

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ARTICLE INFO

Article history:
Received 24 September 2008
Received in revised form
3 January 2009
Accepted 25 February 2009
Published online 23 May 2009

Rapid heating by microwave (MW) and radio frequency (RF) energy offers the possibility to reduce thermal treatment times in post-harvest pest control of mangoes. In order to understand interaction between the fruit and electromagnetic energy, dielectric properties (DPs) of mangoes were measured using an open-ended coaxial-line probe with an impedance analyzer. The influence of frequency (1–1800 MHz), temperature (20–60 °C) and ripening (16 days storage at 21 °C) on dielectric constant (ε') and loss factor (ε'') was evaluated. Additionally, moisture content, soluble solids, acidity, pH, maturity index and electrical conductivity of the mango fruit after 0, 4, 8 and 16 days of storage were determined. DP values decreased with increasing frequency, but this reduction was larger for the loss factor than for the dielectric constant. Loss factor increased but dielectric constant decreased with increasing temperature. Both ε' and ε'' values decreased with storage time, caused mainly by reduced moisture content and increased pH. According to calculations, RF energy at 27.12 MHz has a six times greater penetration depth in mangoes compared to MW energy at 1800 MHz at 20 °C. Values of ε'' calculated from measured electrical conductivities in mango tissues matched well with the experimental ε'' values at frequencies lower than 300 MHz, indicating a dominant ionic conduction effect at these frequencies. DP measurements of mangoes in storage can be useful in selecting the optimal ripening stage at which dielectric heating is suited for postharvest pest control.

1. Introduction

Mango fruit (*Mangifera indica*) is vulnerable to attack by quarantine pests, mainly the Mexican fruit fly, *Anastrepha ludens* (Loew), and the fly of the plum and mango, *Anastrepha obliqua* (Macquart). In Mexico, several pre-harvest control practices are used to avoid the presence of fly eggs and larvae in fruits, including traps, sterile insect technique and biological control

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1537-5110/$ – see front matter
doi:10.1016/j.biosystemseng.2009.02.015

(CESAVEG, 2004). However, these methods are not adequate to completely control the pests. Effective pre-shipping postharvest treatments are required for exported fruits to meet the quarantine regulations of importing countries.

Dielectric heating using radio frequency (RF) and microwave (MW) energy has been studied as a possible disinfestation treatment for several commodities. Nelson (1996) reviewed treatments at different frequencies and temperatures proposed for control of several pests in wheat and flour. RF energy has been studied in pilot scale systems against codling moth in cherries (Ikediala *et al*., 2002) and apples (Wang *et al*., 2006), and against navel orange worm in in-shell walnuts (Wang *et al*., 2001, 2002). To develop a treatment protocol based on RF or MW heating, the first step is to gain knowledge of the dielectric properties (DPs) of the fruit. Those properties provide necessary information about the interaction between the biological material and the electromagnetic energy (Ikediala *et al*., 2000; Wang *et al*., 2003).

The DPs of fruits are parameters that determine the coupling and distribution of electromagnetic energy during dielectric heating. Permittivity is a complex quantity that can be used to calculate reflection of electromagnetic waves at interfaces and the attenuation of the electromagnetic energy within materials. The relative complex permittivity, ε_r, is represented as

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

where ε' and ε'' are the dielectric constant and loss factor, respectively, and $j = \sqrt{-1}$. The real part, the dielectric constant, describes the ability of a material to store energy and influences the electric field distribution of waves travelling through the material. The imaginary part, the loss factor, influences both energy absorption and attenuation, and describes the ability to dissipate energy in response to an applied electric field, which commonly results in heat generation (Mudgett, 1986).

Several techniques can be used to measure the DPs of a material. These techniques include resistivity cell, parallel plate, lumped circuit, coaxial probe, transmission line, cavity resonator, and time domain spectroscopy, each having unique advantages and disadvantages (Içıer and Baysal, 2004). Among these techniques, open-ended coaxial probes have been the most commonly used method to determine the DPs of high loss liquid and semi-solid foods (Nelson *et al*., 1994; Herve *et al*., 1998), and fresh fruits and vegetables (Nelson and Bartley, 2000; Wang *et al*., 2005). This method is convenient, relatively easy to use, and often little or no sample preparation is required.

Dependence of DP of fresh fruits on frequency, temperature, and moisture content has been reported in the literature over the last decade (Ikediala *et al*., 2000; Feng *et al*., 2002; Nelson, 2003; Wang *et al*., 2003; Venkatesh and Raghavan, 2004; Wang *et al*., 2005). However, no data have been reported for mangoes as influenced by temperature and maturity during storage.

The life span of fruits and vegetables consists of three major physiological stages, namely, maturation, ripening and senescence. The maturation stage refers to the time when the fruit is ready for harvesting. Ripening follows maturation, during which the fruit is edible as indicated basically by taste. The last stage is senescence, when a natural degradation of the fruit results in loss of texture or flavour (FAO, 2003). The influence of storage on the DP of fresh fruits has been recently discussed. Guo *et al*. (2005) determined electrical properties of apples at 10 kHz in connection with storage and physiological properties. Lleo *et al*. (2007) studied internal quality of peaches at two seasons after harvesting using MW spectroscopy. Furthermore, Guo *et al*. (2007) found that the DPs of apples remained practically constant over 10-week storage.

The objective of this study was to study the effect of the frequency, temperature and ripening on the DPs of mangoes in storage and to identify the fruit ripening stage and optimal frequency range for the use of dielectric heating as an approach to potential postharvest disinfestation.

2. Material and methods

2.1. Sample preparation

Mangoes (*M. indica* cv. 'Tommy Atkins') imported from Mexico were acquired from a local grocery store in Pullman, WA. Green and immature fruits were sorted and considered as at day 0 for storage at room conditions. The mangoes were stored at 21 °C and selected samples taken on day 0, 4, 8, or 16 of storage for experiments. For each storage period, one mango was peeled and the pulp was blended to obtain one puree sample. Because of the thin peel, the DP of mango pulp could be representative of whole fruits as reported for similar fresh fruits, such as apples, persimmons and peaches (Wang *et al*., 2003; Birla *et al*., 2008).

2.2. Mango analysis

For moisture determination, 3.5 g puree samples were dried in a vacuum oven at 60 °C for 6 h (AOAC, 1994). Soluble solids were measured in pulp with a hand held refractometer (Model N-1α, ATAGO Co. Ltd., Atago, Japan). Acidity was determined by the titrimetric method (AOAC, 1994) and expressed as percentage of citric acid; pH was measured by direct immersion of an electrode in the mango pulp, using an AP5 pH meter (Fisher Scientific, Pittsburgh, PA, USA) after calibration with the buffers at pH 4.0, 7.0 and 10.0. All the tests were conducted in duplicate. The °Bx/acidity ratio was calculated as a maturity index for the fruit (FAO, 2003).

2.3. Dielectric properties measurements

Dielectric constant (ε') and loss factor (ε'') of mango pulp from 1 to 1800 MHz were measured with an open-ended coaxial probe (HP 85070B, Hewlett–Packard, Fullerton, CA) connected to an impedance analyzer (4291B, Agilent Technologies, Inc., Palo Alto, CA, USA). The probe was calibrated with air, an electrical short fitting, and deionized water at 25 °C prior to the measurements. Typical error of the system was about 5% after standard calibration. Further comparisons of DPs of the butyl alcohol at 20 °C between this system and standard values was made to ensure that the measurement results obtained by the impedance analyzer were reliable and the sample size in the cell was adequate for DPs' measurements (Wang *et al.*, 2003). A custom-made test cell was used for holding samples during measurement. Data were acquired with the Dielectric Measurement Software (Innovative Measurement Solutions, Portsmouth, VA, USA). The detailed procedure of measurements and description of the test cell can be found elsewhere (Wang *et al.*, 2003).

The sample temperature in the test cell was controlled using an ethylene glycol bath (Model 1157, VWR Scientific Products, Niles, IL, USA) and held at 20, 30, 40, 50 and 60 °C. The above temperatures covered the maximum range for complete control of the targeted insects in fruits. About 10 min were needed for the samples to reach the next temperature level, during which time the sample centre temperature reached that of the heating medium temperature. DPs at every temperature were obtained from duplicated puree samples.

2.4. *Electric conductivity measurements and relation with loss factor*

Electrical conductivity (σ) of the mango puree was measured using a conductivity meter (CON500, Cole Parmer Instrument Co., Vernon Hills, IL, USA). A platinum/epoxy conductivity probe was used and the equipment was pre-calibrated with the 1500 μS cm^{-1} conductivity standard. About 32 g mango puree was transferred to a small beaker and the probe was immersed in the puree. The beaker was covered with a paraffin film to avoid water evaporation. The beaker with the immersed probe was introduced in a water bath (Digibath, Laboratory Devices, Inc., Holliston, MA, USA). The electric conductivity was measured every 2 °C from 20 to 60 °C. Measurements were carried out in duplicated samples.

Based on the dielectric theory, the loss factor of a material in the frequency range of practical interest in RF and MW heating applications is contributed by the sum of the two predominant mechanisms: dipolar polarization and ionic conduction. The loss factor attributed to ionic conduction (ε''_σ) is directly related to the electrical conductivity by (Metaxas and Meredith, 1993):

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

where σ is the electric conductivity (S m^{-1}), ε_0 is the free space permittivity (8.854×10^{-12} F m^{-1}) and f is the electromagnetic frequency (Hz). Using Eq. (2), the loss factor due to ionic conduction was calculated and compared with the experimental ε'' values acquired from the impedance analyzer.

2.5. *Penetration depth*

It has been reported that RF energy has larger penetration than MW in fresh fruits and nuts, due to longer wavelengths in the RF range (Tang *et al.*, 2000; Wang *et al.*, 2003). To select the optimal frequency for dielectric heating, the DPs of mangoes were used to estimate the penetration depth of electromagnetic power in the fruit by (von Hippel, 1954):

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

where d_p is the penetration depth (m) and c is the speed of light in free space (3×10^8 m s^{-1}).

2.6. *Statistic analysis*

An ANOVA and Tukey's pairwise comparison were conducted to analyze the results using the Minitab Release 14.0 software. The means were separated at the significant level of $p = 0.05$.

3. Results and discussion

3.1. *Mango physiology and ripening*

Moisture content, soluble solid, titratable acidity, pH and maturity index of mangoes are summarized in Table 1. Moisture content and acidity decreased while soluble solid, pH and maturity index increased over the 16 day storage period ($p < 0.05$). These were caused by the metabolism of fruits during ripening (Jagtiani *et al.*, 1988).

Measured values (86.26% of moisture content, 12.2 °Bx, 1.16% of acid citric and pH of 3.4) on day 0 are common of mango fruit at physiological maturity, while values on day 8 are indicators of quality for mango consumption (ripeness stage). Values on day 16 (low moisture, low acidity and high pH) are indicators of the senescence stage.

3.2. *Influence of the temperature and frequency on the dielectric properties*

DPs of mangoes (day 0) for two RF frequencies (27.12 and 40.68 MHz) and two MW frequencies (915 and 1800 MHz) at five different temperatures are summarized in Table 2. These four frequencies are allocated for industrial, scientific and medical use by the Federal Communications Commission

Table 1 – Moisture, soluble solids, acidity, pH and maturity index of mangoes through storage at 21 °C

Storage day	Moisture content (% wb)	Soluble solids (°Bx)	Titratable acidity (% citric acid)	pH	Maturity index
0	86.26 ± 0.05^a	12.2 ± 0.28^a	1.16 ± 0.15^a	3.45 ± 0.02^a	10.59
4	85.03 ± 0.64^b	13.2 ± 1.31^{ab}	0.65 ± 0.01^b	3.75 ± 0.13^a	20.19
8	83.82 ± 0.34^c	15.1 ± 0.42^{bc}	0.13 ± 0.02^c	4.63 ± 0.05^b	116.75
16	81.91 ± 0.21^d	16.6 ± 0.28^c	0.09 ± 0.04^c	5.52 ± 0.54^c	208.42

Means with the same letter means there is no significant difference ($p > 0.05$).

Table 2 – DPs of mango pulp (day 0) at selected frequencies and temperatures

Property	Temperature (°C)	Frequency (MHz)			
		27.12	40.68	915	1800
Dielectric constant	20	83.1 ± 1.0	79.8 ± 0.5	74.0 ± 2.7	70.9 ± 2.0
	30	81.7 ± 1.4	78.0 ± 0.8	71.9 ± 2.9	69.0 ± 2.2
	40	80.5 ± 1.8	76.1 ± 1.2	69.5 ± 3.0	66.9 ± 2.4
	50	79.8 ± 2.5	74.7 ± 1.6	67.3 ± 3.1	65.0 ± 2.5
	60	78.9 ± 2.8	73.1 ± 1.7	65.0 ± 3.1	62.9 ± 2.6
Loss factor	20	250.1 ± 11.0	161.5 ± 7.1	13.8 ± 1.0	14.7 ± 1.2
	30	293.5 ± 13.6	189.5 ± 8.8	14.2 ± 1.1	13.8 ± 0.8
	40	346.4 ± 16.4	223.5 ± 10.7	14.9 ± 1.2	13.2 ± 0.3
	50	404.6 ± 9.6	270.1 ± 0.1	16.0 ± 1.4	12.9 ± 0.0
	60	466.0 ± 28.6	300.5 ± 18.6	17.5 ± 1.6	13.2 ± 0.0

(USDA, 2000). Both dielectric constant and loss factor decreased with increasing frequency (Table 2 and Fig. 1). With increased temperature, the dielectric constant decreased but the loss factor increased at a fixed frequency. Values of ε' and ε'' for mangoes were similar to those reported by Wang *et al.* (2003) for oranges, with the dielectric constant ranging between 75.8 and 84 and loss factor values from 223.3 to 418.4 at 27 MHz. Because of similar dielectric constants over the test frequency range, the value of loss factor becomes more important in evaluating heating uniformity throughout the fruit and possible differential heating of insect *vs.* the host fruits.

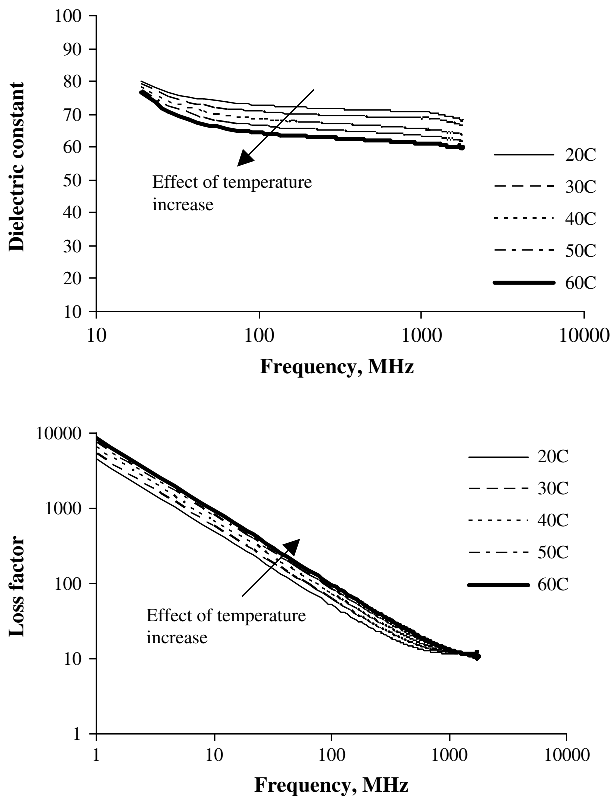

Fig. 1 – Effect of temperature and frequency on the dielectric constant and loss factor of mango pulp on day 4 of storage at 21 °C.

Fig. 1 shows an example of the loss factor for mangoes as influenced by temperature on day 4 of storage. Similar behaviours were observed for other storage times. For clarity, dielectric constant data for frequencies between 1 and 10 MHz were not included in Fig. 1a. In general, ε' decreased with increasing temperature, while ε'' increased with temperature at frequencies lower than 300 MHz. This general trend was in agreement with that reported by Ohlsson *et al.* (1974), who found the same tendency for food materials at frequencies lower than 2800 MHz. The increasing loss factor of fresh fruits with temperature was due to increased ionic conductivity as a result of reduced viscosity at high temperatures (Tang, 2005; Wang *et al.*, 2005).

Both DPs for mangoes decreased with the frequency, but this reduction was larger for the loss factor than for the dielectric constant. The influence of the frequency on the DPs of foods has been discussed by Ryynänen (1995) who concluded that for moist foods, the loss factor increases with decreasing frequency.

3.3. *Electrical conductivity*

The electrical conductivity of mangoes increased with increasing temperature for all storage times (Table 3). The values for 60 °C were about twice those measured at 20 °C. The electrical conductivity decreased with the increasing storage time until day 8 of storage, the values were not significantly different between days 8 and 16 at each temperature ($p > 0.05$). A positive linear correlation between electrical conductivity and temperature was observed for tomato and orange juices by Palaniappan and Sastry (1991).

Fig. 2 shows calculated ε''_σ (from Eq. (2)) and measured ε''_σ values for mangoes after different days of storage. Predicted loss factor values based on the electrical conductivity measurements matched well with the experimental data at frequencies lower than 300 MHz, which can be interpreted as indicative of predominant ionic conduction mechanism at these frequencies. The observation agreed with those of Ryynänen (1995), Guan *et al.* (2004) and Wang *et al.* (2005) who reported that the ionic conductivity dominated the loss at lower frequencies, while for higher

Table 3 – Electrical conductivity (mS cm^{-1}) of mango pulp at different temperatures during 16 days of storage at 21 °C

Storage time (days)	Temperature (°C)				
	20	30	40	50	60
0	3.39 ± 0.02^a	4.09 ± 0.01^a	4.91 ± 0.02^a	5.93 ± 0.02^a	6.95 ± 0.08^a
4	2.48 ± 0.30^b	2.97 ± 0.39^b	3.60 ± 0.50^{ab}	4.37 ± 0.62^{ab}	5.19 ± 0.72^{ab}
8	2.00 ± 0.26^b	2.32 ± 0.37^b	2.82 ± 0.49^b	3.38 ± 0.61^b	3.96 ± 0.69^b
16	2.08 ± 0.03^b	2.56 ± 0.11^b	3.06 ± 0.12^b	3.64 ± 0.05^b	4.16 ± 0.07^b

Means with the same letter means there is no significant difference between values at the same temperature ($p > 0.05$).

frequencies, dipolar relaxation losses were more important. Ragni *et al.* (2007) analyzed the frequency value at which the mechanism changes from ionic conduction-dominated to a rotational-dominated behaviour in hen egg's yolk. For yolk, the observed frequency was 100 MHz, lower than the observed value for mangoes (300 MHz) in this study.

3.4. *Influence of the storage time on the dielectric properties*

Values for ε' and ε'' of mangoes decreased with storage time (Fig. 3). In general, DPs of foods decreased quickly with decreasing moisture content to a critical moisture point (Tang, 2005). Thus, the decreasing tendency was mainly attributed to reduced moisture content and increased pH.

DPs of mangoes were affected by storage time during the first 8 days, but there was no significant difference between 8 and 16 days' storage ($p > 0.05$). From Fig. 3, higher loss factors were observed on day 0 (physiological maturation) in comparison with days 4 and 8 (ripening) or 16 days of storage (senescence). Thus, if dielectric heating would be applied for mangoes, the best ripening stage is the closest to the harvest time, when the loss factor is larger and the heat generation is higher. Furthermore, this period would be also easy to handle the fruits and conduct RF treatments without damaging fruit quality.

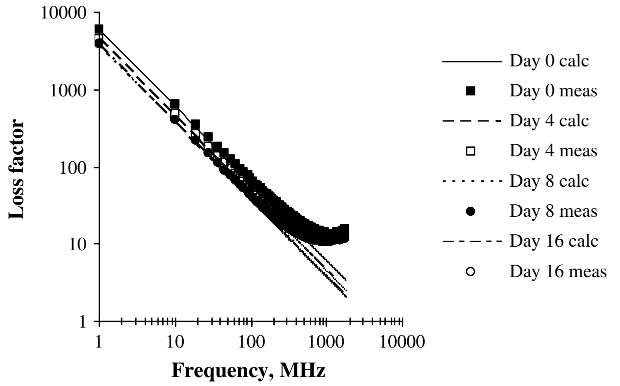

Fig. 2 – Calculated (cals) and measured (meas) loss factor values of mango pulp stored for 16 days at 21 °C. Calculations and measurements were carried out at 20 °C.

Fig. 4 shows the relationship between the mango loss factor and its maturity index over 16 days storage. A significant decrease was observed from days 0 to 4 ($p < 0.05$) and a slight decay followed until day 8. There was no important change between 8 and 16 days storage. An empirical correlation ($y = 313.19x^{-0.1513}$) was obtained using the power law decay, which fitted well the data ($R^2 = 0.857$). On the other hand, it was impossible to relate the dielectric constant to

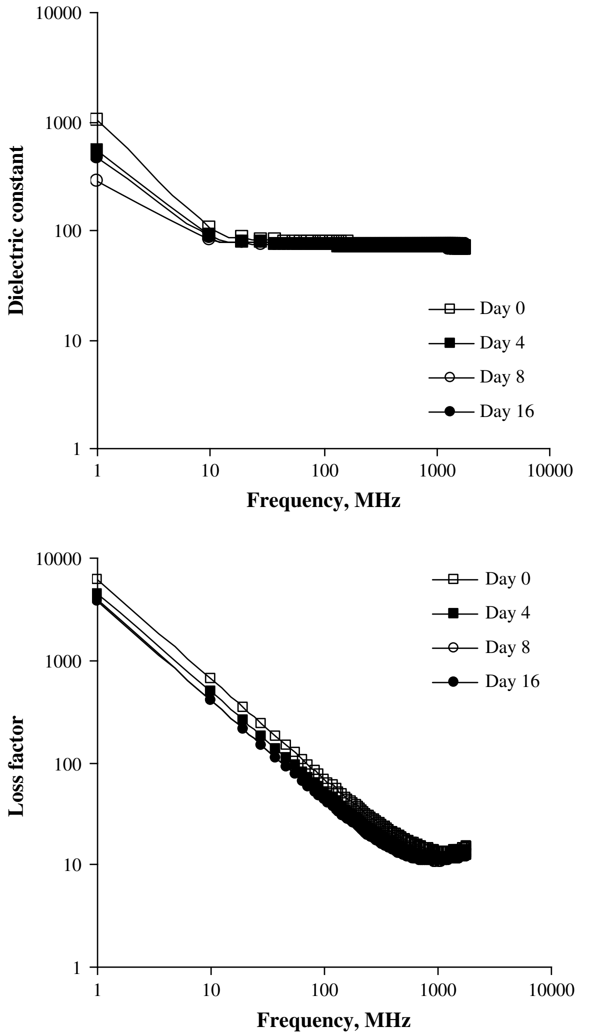

Fig. 3 – Comparison of DPs (measured at 20 °C) on mango pulp at different storage times.

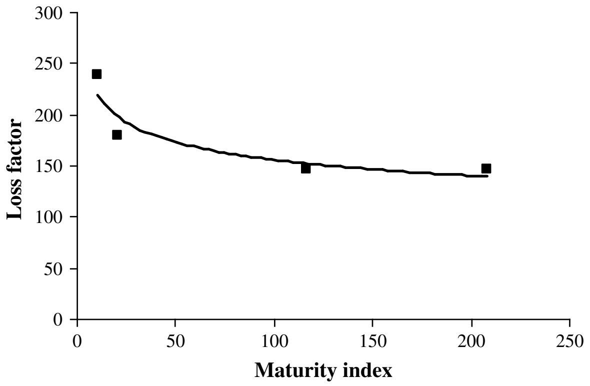

Fig. 4 – Relation between loss factor (experimental data at 27.12 MHz and 20 °C) and maturity index (°Bx/acidity) for mangoes through 16 days storage at 21 °C ($y = 313.19x^{-0151}$).

a mango maturity parameter. Similar disappointment was reported by Guo *et al.* (2007) when trying to relate fresh apples' DPs to soluble solid content, moisture content or pH without finding high correlations.

3.5. *Power penetration depth in mango puree*

Calculated power penetration depths in mangoes at selected RF and MW frequencies are listed in Table 4. The penetration depth, in general, decreased with increasing frequency and temperature. For example, the penetration depth at 27 MHz was six times larger in mangoes compared to that at 1800 MHz at 20 °C, suggesting that a larger fruit could be treated in RF systems. The penetration depths at 27 MHz calculated in this study were lower than those reported by Wang *et al.* (2003) for apples (15.2 cm for Golden Delicious and 18.9 cm for Red Delicious), but similar to those for orange (10.1 cm) and higher than the value reported for cherries (8.5 cm).

The penetration depth in mangoes on day 0 was 9.26 cm at 27.12 MHz, and 3.35 cm at 915 MHz, thus larger penetration (almost three times) was obtained for RF compared with MW frequencies. RF heating should offer advantages over MW treatments, because the limited penetration depth in the latter method which could result in non-uniform heating in large fruits, such as mangoes.

Table 4 – Wave penetration depth in mangoes (day 0) at selected frequencies at different temperatures

Frequency (MHz)	Penetration depth (cm)				
	20 °C	30 °C	40 °C	50 °C	60 °C
27.12	9.26	8.33	7.50	6.82	6.27
40.68	8.28	7.36	6.56	5.78	5.40
915	3.35	3.13	2.92	2.68	2.43
1800	1.52	1.59	1.64	1.66	1.60

4. Conclusions

DPs of mangoes were determined with the open-ended coaxial-line probe technique over 1–1800 MHz and 20–60 °C. Storage time reduced the DP values over 16 days at 21 °C. Higher loss factor values were obtained in the RF region and on day 0, in the physiological maturation stage of the fruit, compared with those values determined in MW region and on 4–16 days storage, in the ripeness and senescence stages. The close estimation of the dielectric loss factor from the electrical conductivity at different temperatures suggested that ionic conduction dominated the dielectric behaviour in the RF range. The calculated penetration depth in mangoes decreased with increasing frequency and temperature. RF energy penetrates deeper in mangoes compared to MWs and, thus, is more suited for potential postharvest disinfestation treatments of this fruit.

Acknowledgements

Authors thank the financial support from CONACyT (Consejo Nacional de Ciencia y Tecnología, Mexico) for the scholarship and supplemental support to author M.E. Sosa-Morales, and acknowledge grants supports from USDA-CSREES (2004-51102-02204) and USDA-NRI (2005-35503-16223) for Washington State University.

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