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Dielectric properties of ground almond shells in the development of radio frequency and microwave pasteurization

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ABSTRACT

To develop pasteurization treatments based on radio frequency (RF) or microwave energy, dielectric properties of almond shells were determined using an open-ended coaxial-probe with an impedance analyzer over a frequency range of 10–1800 MHz. Both the dielectric constant and loss factor of almond shells decreased with increasing frequency, but increased with increasing temperature and moisture content. The absolute value of the slopes of log–log plots between loss factor and frequency increased with increasing temperature at low frequencies, especially at high temperatures and moisture contents. The effective electrical conductivity of shell samples was close to zero at the lowest moisture content (6% w.b.) and 3–9 times larger at 90 °C than 20 °C for the highest moisture content (36% w.b.). A good linear relationship was observed between permittivity and density at 1800 MHz. The power penetration depths at RF range (27 and 40 MHz) were about 6–24 times as deep as those for microwave frequencies (915 and 1800 MHz) at each corresponding temperature and moisture content. It is likely that RF energy may provide uniform heating and high throughput treatments for controlling *Salmonella* in in-shell almonds after washing.

1. Introduction

Almonds are a leading horticultural export for the United States, with about 70% of the total crop shipped for export to more than 80 countries (ABC, 2005). A major concern for raw almonds is possible in-field contamination of pathogenic bacteria, such as of *Salmonella enterica* Serovar Enteritidis. Both epidemiological and environmental investigations confirm that the contamination of almonds occurs during harvest when almonds fall to the ground after mechanical shaking (Isaacs et al., 2005). Thus, the almond shell is the primary point of contamination. Two outbreaks of *Salmonella* caused by consumption of raw almonds have forced the almond industry to seek effective pasteurization processes (CDC, 2004). Because almond shells are porous, they conduct heat poorly when using conventional heating methods, such as forced hot air. Microwave (MW) and radio frequency (RF) treatments may be possible solutions. Those treatments have been proposed to control pathogens in other agricultural and food materials due to rapid volumetric heating (Nelson et al., 2002; Lagunas-Solar et al., 2005; Luechapattanaporn et al., 2005; Gao et al., 2011). In developing such treatments for almond pasteurization, determining the dielectric properties of almond shells is necessary to understand the interactions of the product with electromagnetic energy and estimating the penetration depth in industrial applications.

Thermal resistance of *Salmonella* is several orders of magnitude higher in a dry environment than in a wet environment (Barrile and Cone, 1970; Archer et al., 1998). One potential method to reduce the thermal resistance of *Salmonella* prior to dielectric heating is to add moisture to the almond shell where the contamination occurs. The higher moisture contents of the shell should result in preferential dielectric heating, leading to effective inactivation of pathogens. In addition, as vapor pressure within the almond shells increased with increasing temperature, surface moisture may rapidly be removed. Therefore, it is essential to explore the dielectric properties of almond shells as influenced by moisture content.

Knowledge of dielectric properties is important in developing effective MW and RF treatments with an appropriate heating uniformity over the target product volume because they influence the absorption of electromagnetic energy and conversion to heat (Sosa-Morales et al., 2010). Those dielectric properties of the most interest are the dielectric constant ε' and the dielectric loss factor ε'', the real and imaginary components, respectively, of the

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equation that defines the relative complex permittivity ε as shown below:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1)$$

where $j = \sqrt{-1}$. The open-ended coaxial probe method is commonly used to measure the dielectric properties of high-moisture agricultural products (Engelder and Buffler, 1991; Feng et al., 2002; Ikediala et al., 2000; Nelson, 2005; Wang et al., 2003, 2005). But the major challenge for this probe method is to directly measure dielectric properties of low-moisture products, such as almonds, since it requires a close contact between the flat tip of the probe and the irregularly shaped samples. This measurement problem has been solved by using a ground sample and matching the true density of the sample, resulting in effective and reliable dielectric properties of low-moisture products, such as wheat and legumes (Nelson, 1984; Guo et al., 2008, 2010; Nelson and Trabelsi, 2006; Jiao et al., 2011).

Dielectric properties have been determined for dry products, including bean (Berbert et al., 2002), coffee (Berbert et al., 2001), flaxseeds (Sacilik et al., 2006), grain seeds or flour (Lawrence et al., 1990; Trabelsi and Nelson, 1998; Nelson and Trabelsi, 2006), and legume flours (Guo et al., 2008, 2010). Dielectric properties of almond and walnut kernels have also been reported (Kraszewski and Nelson, 1992; Boldor et al., 2004). Wang et al. (2003) reported that dielectric properties of almond kernels at low moisture content (3% w.b.) had a similar trend to those of walnuts, in which the peak value for loss factors decreased from 3.6 to 1.9 while the frequency corresponding to the peak value shifted from 590 to 890 MHz as the temperature increased from 20 to 60 °C. But no dielectric property data have been reported in the literature for almond shells as related to RF and microwave pasteurizations.

The objectives of this study were: (1) to measure dielectric properties of almond shells at the frequency range of 10–1800 MHz, four moisture contents (6–36% w.b.), and temperatures ranging from 20 to 90 °C, (2) to determine effects of ionic conductivity on the correlation between the loss factor and the frequency as influenced by temperature and moisture content, (3) to develop correlations between dielectric properties and the measured density of almond shell samples for bulk treatments, and (4) to evaluate the penetration depth of electromagnetic energy into the almond shells at 27, 40, 915 and 1800 MHz frequencies commonly used for practical RF and microwave heating applications.

2. Materials and methods

2.1. Measurements of density and moisture content

In-shell almond was obtained from Almond Board of California, Modesto, CA, USA. The samples were cracked manually for collection of the shells. Four moisture contents were selected (6%, 16%, 26%, and 36% w.b.), covering the possible moisture range needed to inactivate *Salmonella* in almond shells. To obtain the desired moisture levels, both intact shell and ground shell samples (100 g) at the initial moisture level of 6% w.b. were mixed with predetermined amounts of distilled water and sealed in polyethylene bags. The samples were stored at 4 °C for 7 days and the bags were shaken two times every day to help distribute the moisture uniformly throughout the sample. The samples were placed at room temperature for 1 day before measuring moisture content.

The true density of almond shell is defined as the ratio of the shell mass to the solid volume occupied by the shell samples. The shell volume and its true density were determined using the liquid displacement method. Toluene (C_7H_8) was selected instead of water because its low surface tension allows it to fill slight irregularities in the shell surface and little toluene was absorbed by the shell during the short time (2 min) required for measurement (Öğüt, 1998). The true density was determined by dividing the mass of whole shell samples (25 g) by the volume of toluene displaced by these samples in 100 ml pycnometers as described in Guo et al. (2008). Moisture content of the shell on a wet basis (w.b.) was determined in a vacuum oven at 100 °C and 75–85 kPa for 1 h using a modified standard oven method (AOCS, 1997). Measurements were conducted with three replicates.

Shell samples of 6% w.b. moisture content were ground into meal using a coffee grinder (ID557, Mr. Coffee, Guangzhou, China) and then passed through a No. 18 mesh (16 Tyler) to ensure sample consistency. Moisture contents were then adjusted and measured as described above for whole shell samples. In order to match the true density of the almond shell at any given moisture content, a predetermined weight of ground shell was placed in a metal cylindrical holder 10.0 cm in height and inner diameter of 2.1 cm (Guo et al., 2008). The ground samples were manually compressed using a hydraulic press (Fred S. Carver Inc. Summit, NJ, USA) to the level determined to provide the needed density (about 4 cm in height), but compression was stopped if water was expressed from the samples. The actual bulk density of the ground samples was recorded and calculated using the sample weight and volume over three replicates.

2.2. Dielectric properties measurements

Dielectric properties of the ground almond shell samples (the actual bulk density from 0.5670 to 0.7139 g cm^{-3}) were measured in two replicates at 20, 30, 40, 50, 60, 70, 80, and 90 °C between 10 and 1800 MHz using an open-ended coaxial probe system. This system consisted of an Agilent 4291B impedance analyzer (Agilent technologies, Palo Alto, CA), a custom-built stainless steel test cell, and a Hewlett Packard 850708B dielectric probe kit. The test cell was designed to allow conditioning of samples to the selected temperatures before each measurement. Detailed information on the system is provided in Wang et al. (2003). After the ground samples were placed in the sample cell, about 0.2 g ground shell was added on the top of the compressed sample to ensure a good contact with the coaxial probe via a pressure spring. Sample temperature was controlled by circulating a solution of 10% water and 90% ethylene glycol through a jacket of the cell from a water bath (model 1157, VWR Scientific Products, Niles, IL, USA). A pre-calibrated type-T thermocouple temperature sensor was used to monitor the central sample temperature.

Before the dielectric properties measurements, the impedance analyzer was warmed up for at least 1 h and then calibrated following the standard procedure described by Wang et al. (2003). After each measurement, the water bath was adjusted to the next temperature level, with sample temperatures reaching the desired level in about 10 min. For each replicate, the probe and the sample cell were cleaned with de-ionized water and wiped dry. Mean values and standard deviations were calculated from the two replicates.

2.3. Power penetration depth

The penetration depth (d_p in m) of RF and MW power is defined as the depth where the power is reduced to $1/e$ (e = 2.718) of the power entering the surface. It was calculated according to Von Hippel (1954):

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

where c is the speed of light in free space (3×10^8 m s^{-1}) and f is the frequency (Hz). After obtaining the dielectric properties, the power penetration depths into the shell samples were calculated at four commercially useful frequencies (27, 40, 915 and 1800 MHz), three temperatures (20, 60, and 90 °C) and all four moisture contents.

3. Results and analyses

3.1. Moisture content dependant density

The true density of whole intact shells and the bulk density of the ground almond shell samples are listed in Table 1. Density of whole shells increased with increasing moisture content from 6% to 36% w.b. The following linear equation was obtained to describe the density of whole shells, ρ_t (0.9623–0.9988 g cm^{-3}), as a function of moisture content, MC:

$$\rho_t = 0.9543 + 0.0012\text{MC}\ (R^2 = 0.997, 0.06 \leqslant \text{MC} \leqslant 0.36) \quad (3)$$

Aydin (2003) also observed a linear increase in almond density with increasing moisture content from 2.8% to 25% d.b. The density of ground shell samples was lower than the density of whole shells at each moisture level (Table 1). The differences were probably caused by air voids in the sample and sample relaxation after removal of the compression force at low moisture contents. Especially at higher moisture levels, the compression was stopped when the water was expressed from the samples. The required sample height was not reached, resulting in lower density levels when compared to the desired values. A similar experimental design underestimated the density of legume flour samples (Guo et al., 2008) and caused the expulsion of water from chestnut samples (Guo et al., 2011). In the current study, the sample at 6% moisture could be compressed more than samples at 16–36% moisture without the expulsion of water, resulting in a higher density than the 16% moisture sample. Within the 16–36% moisture range, however, density increased as moisture content increased, although density was less than expected one because of the expulsion of water.

3.2. Dielectric properties as influenced by frequency, temperature and moisture content

Dielectric properties of almond shells at the selected frequencies, moisture levels and temperatures are listed in Table 2. Generally, both the dielectric constant and loss factor decreased with increasing frequency, especially at high temperatures and moisture contents. These trends were similar to those of chickpea, green pea, lentil and soybean flour (Guo et al., 2010) and wheat flour within the same frequency range (Nelson and Trabelsi, 2006). The mean values of the dielectric constant for the almond shells at 6% w.b. were slightly smaller than those of the almond kernel at 3% w.b. reported by Wang et al. (2003). The loss factor of the almond shell was similar to those of the kernel at the RF range but smaller than those of the kernels at the microwave range, since there was a clear peak around 600 MHz for the kernels (Wang et al., 2003), probably caused by the complex interaction among moisture, density, and temperature. The loss factors of shell samples were also plotted against frequency in a log–log plot at the highest (36% w.b., Fig. 1a) and lowest moisture content (6% w.b., Fig. 1b). Log ε'' had a negative linear relationship with log *f*, especially at high temperatures and low frequencies (e.g. below 200 MHz). The slopes of log ε'' vs. log *f* below 200 MHz in Fig. 1 were calculated and shown in Fig. 2a. The absolute slope values at the highest moisture content first increased with increasing temperature (below 60 °C) and then leveled off. But at the lowest moisture content the absolute slope values generally increased with increasing temperature except for 20 °C. In addition, the absolute slope values at 36% w.b. were about 3–9 times larger than those at 6% w.b., which was mainly caused by the effect of moisture on the ionic conductance of almond shell samples.

The effective electrical conductivity (σ_e) can be estimated from the measured dielectric loss factor using the following relationship for low frequencies of less than 200 MHz (Liu et al., 2009):

$$\log \varepsilon'' = a - b \log f \quad (4)$$

where

$$a = \log \frac{\sigma_e}{2\pi\varepsilon_o} \quad (5)$$

Conductivity of almond shell samples was estimated based on the intercept (a) in Fig. 2a as a function of temperature and moisture content as follows:

$$\sigma_e = 2\pi\varepsilon_0 10^a \quad (6)$$

where ε_0 is the permittivity of free space or vacuum (8.854×10^{-12} F/m).

Fig. 2b shows that these estimated electrical conductivity values increased with increasing temperature at the highest moisture content and were negligible at the lowest moisture content over the measured temperature range. This suggested that low moisture content might result in low mobility of ions, resulting in less heat. Guo et al. (2010) also reported low electrical conductivity at low moisture contents for chickpea, green pea, lentil, and soybean flour.

To better understand the relationships between permittivity, moisture content and temperature, the dielectric constant and loss factor at 27 MHz were plotted as a function of temperature ranging from 20 to 90 °C at four moisture levels (Fig. 3). Both dielectric constants and loss factors increased with increasing temperature and moisture contents. The slopes increased with temperature, particularly at the three highest moisture contents. A short pretreatment wash was shown to increase the almond shell moisture content to 34% w.b. while keeping the almond kernel close to the original level (3% w.b.) (Gao et al., 2011). Thus, RF heating should initially result in higher temperatures in the shell than in the kernel because more RF energy would be absorbed by the higher moisture shells, and should effectively inactivate *Salmonella*. As shell moisture contents decrease due to the drying effect of RF heating, the dielectric constants and loss factors should also decrease, reducing shell temperatures.

3.3. Density dependent permittivity as a function of frequency

Correlations have been reported between the measured dielectric constant ε' and loss factor ε'', each divided by the density in complex-plane plots, resulting in highest coefficient of determination at 1800 MHz (Nelson and Trabelsi, 2006; Guo et al., 2008, 2010). Fig. 4 shows a comparison of complex-plane plots of measured ground shell samples at 1800 MHz at various temperatures and four moisture contents (6%, 16%, 26% and 36% w.b.). All data were distinctly distributed in a linear regression described below:

$$\frac{\varepsilon''}{\rho} = 0.3530\frac{\varepsilon'}{\rho} - 0.5879\ (0.5670 < \rho < 0.7139\ g\ cm^{-3}) \quad (7)$$

Table 1
Densities of whole shells and ground samples at four moisture contents.

Moisture content (% w.b.)	Whole shell [a] (ρ_t, g cm^{-3})	Ground samples [b] (ρ, g cm^{-3})
6	0.9623 ± 0.0085	0.6214 ± 0.0117
16	0.9728 ± 0.0062	0.5670 ± 0.0145
26	0.9863 ± 0.0037	0.6351 ± 0.0121
36	0.9988 ± 0.0052	0.7139 ± 0.0132

[a] True density determined using toluene displacement method.
[b] Bulk density determined by sample volume and weight.

Table 2
Dielectric properties (mean ± SD of replicates) of ground shell sample with four moisture contents at eight temperatures and four frequencies.

Moisture content (% w.b.)	Temp. (°C)	Dielectric constant at frequency (MHz)				Loss factor at frequency (MHz)			
		27	40	915	1800	27	40	915	1800
6	20	2.07 ± 0.00	2.04 ± 0.00	2.03 ± 0.01	1.73 ± 0.02	0.10 ± 0.00	0.10 ± 0.00	0.09 ± 0.00	0.06 ± 0.00
	30	2.07 ± 0.06	2.02 ± 0.06	1.79 ± 0.35	1.73 ± 0.02	0.10 ± 0.01	0.10 ± 0.01	0.08 ± 0.00	0.07 ± 0.00
	40	2.11 ± 0.06	2.07 ± 0.06	1.71 ± 0.24	1.80 ± 0.04	0.10 ± 0.01	0.10 ± 0.01	0.13 ± 0.00	0.07 ± 0.00
	50	2.18 ± 0.06	2.14 ± 0.06	1.78 ± 0.28	1.94 ± 0.23	0.12 ± 0.01	0.12 ± 0.01	0.12 ± 0.00	0.10 ± 0.00
	60	2.28 ± 0.06	2.23 ± 0.06	1.95 ± 0.37	2.09 ± 0.28	0.13 ± 0.01	0.14 ± 0.01	0.15 ± 0.01	0.13 ± 0.00
	70	2.49 ± 0.06	2.42 ± 0.07	2.12 ± 0.35	2.19 ± 0.28	0.19 ± 0.02	0.19 ± 0.01	0.21 ± 0.01	0.19 ± 0.00
	80	2.96 ± 0.08	2.86 ± 0.08	2.40 ± 0.30	2.52 ± 0.20	0.38 ± 0.04	0.36 ± 0.04	0.31 ± 0.01	0.24 ± 0.00
	90	4.42 ± 0.21	4.16 ± 0.19	3.07 ± 0.33	3.09 ± 0.26	1.35 ± 0.18	1.15 ± 0.07	0.55 ± 0.02	0.38 ± 0.00
16	20	2.34 ± 0.08	2.28 ± 0.09	1.86 ± 0.33	2.05 ± 0.04	0.23 ± 0.00	0.23 ± 0.02	0.08 ± 0.01	0.15 ± 0.01
	30	2.58 ± 0.08	2.51 ± 0.10	1.92 ± 0.32	2.09 ± 0.00	0.29 ± 0.04	0.26 ± 0.03	0.20 ± 0.00	0.16 ± 0.01
	40	2.73 ± 0.05	2.65 ± 0.07	2.02 ± 0.33	2.19 ± 0.13	0.37 ± 0.05	0.33 ± 0.05	0.23 ± 0.00	0.22 ± 0.01
	50	2.98 ± 0.04	2.87 ± 0.02	2.18 ± 0.39	2.35 ± 0.16	0.56 ± 0.16	0.48 ± 0.13	0.29 ± 0.00	0.26 ± 0.00
	60	3.51 ± 0.23	3.32 ± 0.18	2.45 ± 0.43	2.61 ± 0.23	1.37 ± 0.08	1.13 ± 0.05	0.39 ± 0.01	0.32 ± 0.01
	70	4.84 ± 0.88	4.43 ± 0.71	2.79 ± 0.83	3.16 ± 0.36	3.79 ± 0.19	2.70 ± 0.50	0.73 ± 0.00	0.53 ± 0.03
	80	9.83 ± 0.68	8.87 ± 0.15	3.84 ± 1.30	4.74 ± 0.11	7.93 ± 1.15	9.16 ± 0.05	1.55 ± 0.00	1.15 ± 0.01
	90	14.12 ± 2.15	13.75 ± 0.86	7.25 ± 0.25	7.47 ± 0.29	27.73 ± 3.30	21.51 ± 1.10	3.35 ± 0.03	2.04 ± 0.03
26	20	6.10 ± 0.18	5.55 ± 0.16	4.13 ± 1.09	3.03 ± 0.03	5.18 ± 0.23	3.95 ± 0.11	0.83 ± 0.14	0.47 ± 0.06
	30	6.09 ± 0.06	5.56 ± 0.04	3.58 ± 0.02	3.41 ± 0.00	4.78 ± 0.11	3.67 ± 0.06	0.68 ± 0.04	0.63 ± 0.02
	40	7.27 ± 0.18	6.54 ± 0.18	3.87 ± 0.26	3.72 ± 0.30	8.65 ± 1.08	6.43 ± 0.70	0.96 ± 0.03	0.78 ± 0.00
	50	9.22 ± 0.08	8.13 ± 0.09	4.46 ± 0.25	4.40 ± 0.26	14.11 ± 2.28	10.36 ± 1.57	1.20 ± 0.16	0.99 ± 0.19
	60	12.00 ± 1.16	10.48 ± 0.77	5.65 ± 0.27	5.48 ± 0.26	21.74 ± 1.35	15.51 ± 0.73	1.82 ± 0.21	1.33 ± 0.06
	70	13.59 ± 1.47	12.32 ± 1.43	7.02 ± 0.22	6.82 ± 0.15	28.16 ± 2.23	19.61 ± 1.14	2.45 ± 0.63	1.78 ± 0.17
	80	16.41 ± 1.68	15.00 ± 1.55	8.18 ± 0.82	8.09 ± 0.65	43.99 ± 1.45	21.38 ± 1.43	2.80 ± 1.54	2.29 ± 1.31
	90	19.47 ± 1.64	17.76 ± 1.46	10.13 ± 1.16	9.83 ± 0.97	68.03 ± 3.23	26.91 ± 2.92	4.41 ± 0.00	2.96 ± 1.16
36	20	8.96 ± 0.10	8.17 ± 0.08	4.87 ± 0.03	4.73 ± 0.11	12.43 ± 0.49	9.12 ± 0.33	1.21 ± 0.01	1.03 ± 0.00
	30	9.57 ± 0.03	8.23 ± 0.69	5.12 ± 0.14	5.43 ± 0.27	14.02 ± 4.80	11.19 ± 1.89	1.34 ± 0.20	1.15 ± 0.00
	40	11.28 ± 0.87	10.17 ± 0.64	6.96 ± 1.60	6.64 ± 1.20	26.20 ± 1.45	19.06 ± 1.78	2.20 ± 0.49	1.57 ± 0.00
	50	13.41 ± 1.46	12.40 ± 1.62	7.82 ± 1.39	7.57 ± 1.14	38.48 ± 1.33	27.67 ± 1.98	2.63 ± 0.35	2.01 ± 0.01
	60	15.70 ± 1.83	13.91 ± 1.18	8.80 ± 1.14	8.56 ± 1.26	49.74 ± 1.69	34.72 ± 1.38	3.17 ± 0.44	2.27 ± 0.00
	70	17.84 ± 1.05	16.77 ± 1.72	9.94 ± 1.14	9.62 ± 1.21	63.02 ± 2.09	37.63 ± 1.64	3.77 ± 0.60	2.63 ± 0.00
	80	22.67 ± 1.63	20.19 ± 1.01	11.31 ± 0.93	11.00 ± 0.75	78.12 ± 2.08	46.36 ± 1.80	4.51 ± 0.35	3.23 ± 0.00
	90	26.91 ± 0.90	24.62 ± 1.36	12.60 ± 0.18	12.22 ± 0.27	92.30 ± 4.66	61.68 ± 2.45	5.08 ± 0.21	3.56 ± 0.00

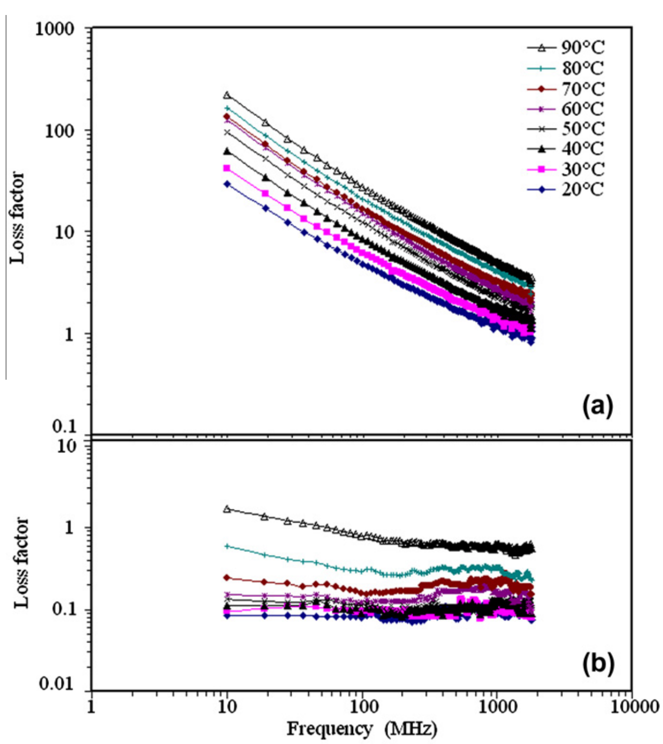

Fig. 1. Frequency dependent dielectric loss factor at moisture contents of 36% (a) and 6% w.b. (b) of the ground almond shell samples and eight temperatures.

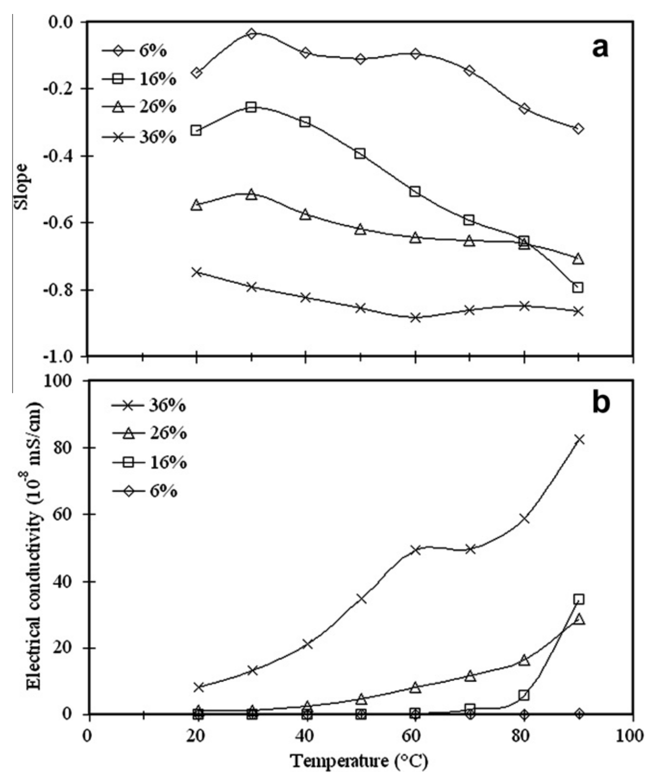

Fig. 2. Slope (a) of log ε″ vs. log *f* (<200 MHz) in Fig. 1 and electrical conductivity (b) as functions of temperature of ground almond shells at the four moisture contents at wet basis.

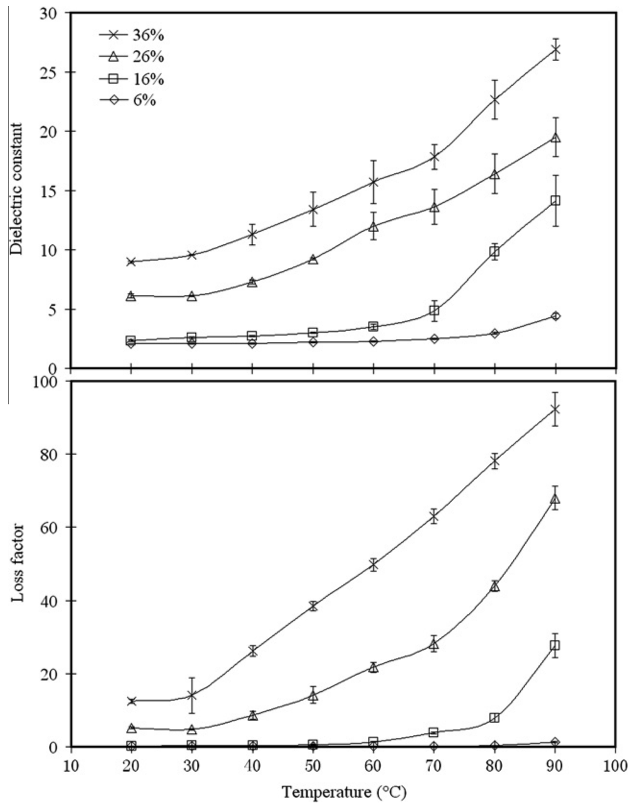

Fig. 3. Dielectric constant and loss factor of the ground almond shell samples as a function of temperature and moisture at 27 MHz.

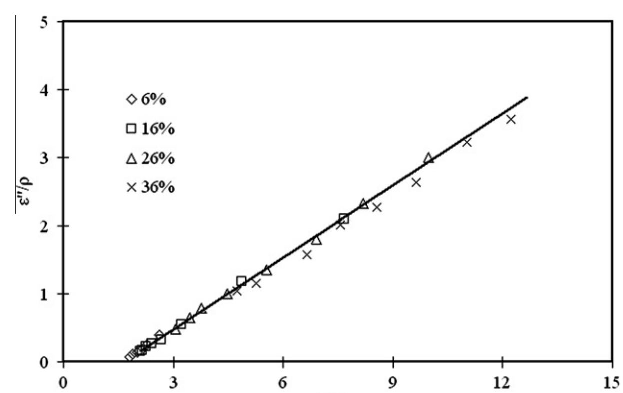

Fig. 4. Complex-plane plot of the ground almond shell samples at 1800 MHz over all measured moisture contents and temperatures.

The regression had a high coefficient of determination ($R^2 = 0.998$) and could be used to estimate the density of the almond shell based on dielectric properties measurements.

3.4. Power penetration depth

Power penetration depths decreased with increasing moisture content, temperature and frequency (Table 3). Generally, electromagnetic energy at radio frequencies (27 and 40 MHz) had greater penetration depths in almond shells than at microwave frequencies (915 and 1800 MHz). For example, the penetration depths for moisture content of 6% w.b. and temperature of 20 °C at 27 MHz were about 40 times larger than those at 1800 MHz. But this ratio was reduced to about six times at moisture level of 36% and 90 °C. This trend for penetration depth in almond shells as influenced by frequency, moisture content, and temperature is similar to that of many agricultural products (Nelson, 1973; Wang et al., 2005; Guo et al., 2008; Jiao et al., 2011). Given that the minimum penetration depth for almond shells is 15 cm (at 36% moisture and 90 °C), it is likely that commercial RF pasteurization treatments could be designed that would provide sufficient throughput with acceptable heating uniformity to control *Salmonella* in in-shell almonds.

Table 3
Penetration depths (cm) calculated from the measured dielectric properties of the ground almond shell samples at four specific frequencies over three temperatures and four moisture contents.

Moisture content (% w.b.)	Temp. (°C)	Penetration depths (cm) at four frequencies (MHz)			
		27	40	915	1800
6	20	2482.1 ± 228.0	1630.7 ± 68.7	80.1 ± 1.6	59.8 ± 0.2
	60	2042.7 ± 206.9	1302.9 ± 113.8	48.1 ± 2.1	29.5 ± 2.2
	90	278.9 ± 43.4	213.4 ± 18.2	16.8 ± 0.8	12.3 ± 0.6
16	20	1169.7 ± 28.5	782.8 ± 44.5	84.3 ± 5.6	25.8 ± 1.1
	60	246.8 ± 6.6	195.3 ± 3.9	21.0 ± 1.3	13.4 ± 0.2
	90	30.3 ± 1.6	24.6 ± 1.4	4.3 ± 0.0	3.6 ± 0.1
26	20	90.7 ± 4.6	75.2 ± 2.8	12.8 ± 0.5	9.8 ± 1.3
	60	34.9 ± 0.8	29.4 ± 0.5	6.9 ± 0.9	4.7 ± 0.3
	90	17.5 ± 0.3	22.2 ± 1.4	3.9 ± 0.2	2.8 ± 0.0
36	20	49.6 ± 1.3	41.8 ± 1.1	9.6 ± 0.0	5.6 ± 0.1
	60	20.7 ± 0.1	17.4 ± 0.2	5.0 ± 0.3	3.4 ± 0.2
	90	15.0 ± 0.4	13.1 ± 0.2	3.7 ± 0.2	2.6 ± 0.0

4. Conclusions

Both dielectric constant and loss factor of almond shell samples decreased with increasing frequency, but increased with increasing temperature and moisture content. The change in permittivity was rapid when temperature was raised above 60 °C, especially at higher moisture contents. The negative slopes of log–log plot between frequencies and loss factor increased with increasing temperature at low frequencies, especially at high temperature and moisture content, which was mainly caused by the ionic conductance. The effective electrical conductivity of shell was negligible at the lowest moisture content but increased nearly 10 times as sample temperatures increased from 20 to 90 °C at the highest moisture content. The good linear relationship between the permittivity at microwave frequency and the actual bulk density could be used to adjust sample dielectric properties. The power penetration depths at RF range (27 and 40 MHz) were much larger than those at microwave frequencies (915 and 1800 MHz) at each corresponding temperature and four moisture contents. The estimated penetration depths in RF systems should allow the development of continuous large scale pasteurization treatments with sufficiently uniform heating for controlling *Salmonella* in in-shell almonds.

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