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ORIGINAL PAPER

Temperature- and Moisture-Dependent Dielectric Properties of Macadamia Nut Kernels

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Abstract Conventional hot air drying for macadamia nuts takes several weeks, generating great interest in developing advanced drying technologies. Radio frequency (RF) and microwave (MW) heating hold potential for providing fast and uniform drying with acceptable product quality. To clearly understand the interaction between electromagnetic energy and macadamia nuts, information on dielectric properties of the kernels is needed for designing a practical and effective drying process. In this study, dielectric properties of the macadamia nut kernels were measured between 10 and 1,800 MHz using an open-ended coaxial-line probe technique at temperatures between 25 and 100 °C and moisture contents between 3 % and 24 % on a wet basis (w.b.). The results showed that both dielectric constant and loss factor of the kernels decreased sharply with increasing frequency over the RF range (10 to 300 MHz), but gradually over the measured MW range (300–1,800 MHz), which were largely enhanced by increasing moisture content and temperature. Penetration depth decreased with increasing frequency, moisture content, and temperature. Based on this study, uniform drying of macadamia nut kernels in thick layers could be effectively developed using RF energy.

Keywords Dielectric properties · Open-ended coaxial probe · Macadamia nut kernels · Dielectric drying

Introduction

Macadamia nuts (*Macadamia tetraphylla*) are grown commercially in Australia, Hawaii, South Africa, and South America. According to the report of International Nut Council (INC), the world macadamia kernel production was estimated to be 26,123 metric tons in 2007/2008. Hawaii was ranked third in world macadamia nut production in 2010 with 3,750 tons of macadamia kernels, valued at US $29.4 million accounting for 14.4 % of the total world production (Nagao 2011). Macadamia nuts are rich in monounsaturated fatty acids, which can potentially lower cholesterol and triglyceride levels, thus reducing the risk of heart diseases (Grag et al. 2003; Borompichaichartkul et al. 2009). Properly processed macadamia nuts provide a uniquely delicate flavor and crunchy texture (Wall 2010).

The moisture content of fresh nuts varies from 15 to 25 % (wet basis, w.b.). The nut kernels must be dried immediately to a moisture content of less than 1.5 % w.b. (Wall and Gentry 2007). Low moisture content is essential to a high kernel recovery rate after cracking, and to obtain desired kernel flavor and texture after processing and storage (Nagao 2011). Macadamia nuts have thick and hard shells, which result in a very long drying cycle, often more than 1 month to complete the industrial drying (Silva et al. 2006).

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After harvesting, in-shell nuts are first air-dried over 3 to 4 weeks until the product moisture content is reduced to 8.26 % w.b. The pre-dried nuts are then delivered to an industrial plant where they are dried by hot air in a silo-type dryer under controlled temperature conditions. This hot air drying process starts at 40 °C and finishes at 60 °C to reduce kernel moisture content to 1.5 % w.b. over about 6 days (Silva et al. 2006). The process occupies enormous area, with extensive handling of the processed material and considerable costs involved. It is desirable to develop advanced heating technologies to speed up the conventional drying process using microwave (MW) or radio frequency (RF) energy (Ramaswamy and Tang 2008). With these methods, MW and RF waves pass through nut shells and provide direct interaction between the electromagnetic field and the nut kernels to remove the moisture from the kernels (Metaxas and Meredith 1983; Zhang et al. 2006). To achieve rapid and uniform MW and RF drying of macadamia nuts, it is essential to know their dielectric properties as affected by temperatures and moisture contents.

Most foods and agricultural products can store and dissipate electromagnetic energy when subjected to MW and RF heating. Knowledge of dielectric properties is most important for dielectric heating (Boyaci et al. 2009; 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 real part, ε', known as the relative dielectric constant, is a measurement of a material's ability to store energy in an applied electrical field. The imaginary part, ε'', known as the relative electric loss factor, measures the energy that is dissipated in the material from the applied electric fields, which typically results in temperature increases in the dielectric material. Many factors, including frequency, temperature and chemical compositions, influence the dielectric properties of foods and agricultural products (Lorrain et al. 1988; Nyfors and Vainikainen 1989; Wang et al. 2003b, c; Tang et al. 2005; Wang et al. 2005, 2011; Li et al. 2011). But moisture content is one of the most important factors in MW and RF drying applications since water molecules have a permanent dipole, which follows the rapidly changing polarity of the alternating electric field. Ionic conduction is another important loss mechanism especially for RF drying (Wang et al. 2003b, 2011):

$$\varepsilon'' = \varepsilon_d'' + \varepsilon_\sigma'' = \varepsilon_d'' + \frac{\sigma}{2\pi f \varepsilon_0} \tag{2}$$

where, subscripts d stands for dipole rotation and σ for ionic conduction (in siemens per meter); f represents the electromagnetic frequency in Hz (in per second); ε_0 is the free space or vacuum permittivity (8.854×10^{-12} F m^{-1}). In MW and RF drying, materials absorb electric field energy and convert it into heat. Dielectric properties are important to assess the energy conversion efficiency and estimate the penetration depth when applying MW and RF drying to a material. They are basic parameters when designing MW and RF drying processes and equipments (Wang et al. 2011).

The open-ended coaxial probe method is a commonly used method to measure the complex dielectric permittivity of many high loss materials since it has broad frequency bands and is easy to use (Wang et al. 2003a, 2005; Silva et al. 2006; Guo et al. 2008, 2010, 2011; Jiao et al. 2011). But it is difficult to directly apply this method to measure the dielectric properties of low moisture products, such as nuts, seeds and legumes, because it requires close contact between the flat tip of the probe and irregularly shaped seeds. This measurement problem has been solved by using a ground sample of the product, which matches the true product density (Guo et al. 2008). This method allows the application of open-ended coaxial probe methods for measuring dielectric properties of dry products (Guo et al. 2008, 2010).

Dielectric properties have been studied over different frequency, temperature and moisture ranges for seed products (Nelson 1973; Inoue et al. 2002; Trabelsi and Nelson 2003; Wang et al. 2003a; Boldor et al. 2004; Sacilik et al. 2007; Hu et al. 2010). Several studies have been reported on dielectric properties of nuts. Wang et al. (2003a) studied dielectric properties of almond and walnut kernels between 1 and 1,800 MHz and at temperatures between 20 and 60 °C but only at one moisture content and a low density level using the open-ended coaxial probe method. Boldor et al. (2004) also reported that dielectric properties of ground shelled Georgia Green peanuts decreased with increasing frequency, and increased with increasing moisture content. Up to now, there is no detailed report on dielectric properties of macadamia nut kernels at different moisture content and temperature levels associated with practical MW and RF drying.

The objectives of this research were (1) to study the dielectric properties of the macadamia nut kernels as influenced by frequency (10–1,800 MHz), moisture content (3–24 % w.b.), and temperature (25–100 °C), and (2) to determine the penetration depth of electromagnetic energy into nut kernels at frequencies of 27.12, 40.86, 915, and 1,800 MHz related to industrial RF and MW drying applications.

Materials and Methods

Materials

Shelled macadamia nuts were harvested in 2009, dried to 1.9 % w.b., and shipped to Washington State University,

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Pullman, WA from one of the major processors (Island Princess Macadamia Nut Company) of macadamia nuts in Hawaii, USA. To prevent moisture change, samples were shipped in sealed aluminum foil laminated paper bags protected by corrugated cardboard cartons. Immediately after receipt, macadamia nut kernels in cartons were refrigerated at 0–4 °C until needed. The sample compositions determined with standard methods are summarized in Table 1.

Sample Preparation and Density Measurement

To obtain samples with six moisture content levels (3, 6, 12, 18, and 24 % w.b.) for dielectric properties measurement, 50 g macadamia nut kernels with the original moisture content of 1.9 % w.b. (Table 1) were placed in a plastic bottle. Pre-determined amounts of deionized water were sprayed on the samples. The bottles were capped, shaken and stored in the refrigerator at 4 °C. The samples were held for 6 days, and shaken three times per day to allow uniform moisture distribution throughout the samples.

Nut kernels have irregular shapes and are relatively small in size. It is, thus, difficult to directly measure the dielectric properties of single kernels using the open-end coaxial probe method (Jiao et al. 2011). Maintaining sample temperature of single kernels at an elevated level during measurement presents additional challenges. For the above reasons, nut kernels conditioned to specific moisture contents were ground into flour in a coffee grinder. According to Berbert et al. (2002), dielectric properties of particulate materials are influenced by sample density. The samples in the holder were then compressed on a hydraulic press (about 4 cm in height) to match the true density of the samples measured at different moisture content as described by Guo et al. (2008).

The true density of nut kernel samples was measured using the liquid displacement method. Toluene was used as the displacement liquid. Each measurement was conducted in triplicate, and the average density was calculated. Detailed measurement procedures can be found in Guo et al. (2008). The determined true densities together with the standard deviations (SD) are summarized in Table 2.

Table 1 Macadamia nut kernels compositions and methods used in the measurements

Compositions	Content (g per 100 g^{-1})	Methods
Carbohydrate	12.9	CFR 101.9
Fat	76.0	AOCS Am 5-04
Protein	7.9	AOAC 950.48
Ash	1.3	AOAC 950.49
Moisture content	1.9	AOAC 934.01

Table 2 The true densities of macadamia nut kernels at five moisture contents

Moisture content (%, w.b.)	Density±SD (g cm^{-3})[a]
3	1.0015±0.0003
6	1.0034±0.0002
12	1.0085±0.0004
18	1.0143±0.0005
24	1.0162±0.0005

[a] Results are the mean values over three independent trials ($N=3$)

Moisture Content Measurement

Moisture content of nut kernels was determined following the AOAC Official Method 925.40 with some modification. Ten grams of kernels ware ground. Two grams of the kernel flour were put into an aluminum container, providing with well-fitting lids. Containers with samples were placed in a vacuum oven, with their lids placed beside them. The oven was brought to 100 °C under pressure ≤21 kPa, and samples were taken out after 7 h drying. Weight changes in samples were used to calculate initial moisture content of the samples before oven drying. Each measurement was conducted in triplicate and the average percentage of moisture content was reported on a wet weight basis.

Dielectric Properties Measurement

An open-ended coaxial-line probe connected to an impedance analyzer (HP4291B, Hewlett Packard Corp., Santa Clara, CA, USA) was used to measure the dielectric properties of compressed sample flours. The impedance analyzer had a measurement frequency range of 1–1,800 MHz.

Prior to the measurement, the impedance analyzer and the computer attached to the analyzer was turned on, and kept in a standby condition for at least 0.5 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 properties from the obtained data. To minimize errors, the impedance analyzer, electric cable and probe were maintained at fixed positions during calibration and measurement.

After following standard calibration procedures, a compressed sample (about 15 g) at one of five different moisture contents (3, 6, 12, 18, and 24 %, w.b.) was placed in a stainless steel sample cell. The design of the cell is described

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in detail in Wang et al. (2003a, b) and Guo et al. (2008, 2010). The sample temperature was raised incrementally to five different levels (25, 40, 60, 80, and 100 °C). About 15 min was needed for the sample temperature to increase from one to the next temperature level. A type-T thermocouple temperature sensor was used to measure the sample center temperature. Dielectric properties measurements were made from 10 to 1,800 MHz, which cover three RF frequencies (13.56, 27.12, and 40.68 MHz) and one MW frequency (915 MHz) allocated by the U.S. Federal Communication Commission for industrial heating applications. Detailed information about the dielectric properties measurement system and procedure can be found elsewhere (Wang et al. 2003a, b; Guo et al. 2008, 2010). Three replicated measurements were made for each moisture content level.

Penetration Depth Calculation

The penetration depth (d_p) of RF and MW power in a material is defined as the distance (in meters) at which an incident electromagnetic power intensity is reduced to $1/e$ (e is equal to 2.71828) of its amplitude at the entering surface (von Hippel 1954). The electric power penetration depth in a material was calculated as follows:

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

where, c is speed of light in free space (3×10^8 m/s). After obtaining the dielectric properties, the penetration depth was estimated for macadamia nut kernels at the four selected frequencies, five moisture contents, and five temperatures.

Statistical Analysis

All the tests were replicated three times. Mean values and standard deviations (SD) were calculated over the replicates for effects of each temperature and moisture level.

Results and Discussions

Frequency-Dependent Dielectric Properties of Nut Kernels

Figures 1 and 2 show the frequency dependence of the dielectric constant and loss factor of macadamia nut kernels as functions of different moisture contents and temperatures. At low moisture levels, such as 3 and 6 % w.b. (Figs. 1 and 2a,b), all the dielectric constant and loss factor values of the nut kernels were less than 9 at all measured temperatures, which were mainly caused by high fat contents in the nut kernel as shown in Table 1 (Tang et al. 2002). The mean dielectric properties values of the macadamia nut kernels were in the same magnitude as the dielectric constant (2.7) and loss factor (0.3) for walnut kernels at 2,000–3,000 MHz reported by Olmi et al. (2000). Similar values of dielectric properties were also obtained by Sacilik et al. (2007) for safflower seed at moisture contents of 5.1 and 7.5 % w.b. and 10 MHz. On the other hand, both the dielectric constant and loss factor values peaked in the range between 1,000 and 1,600 MHz. The peak values clearly existed at low moisture levels, such as 3 % w.b., but completely disappeared when the moisture content was equal to or higher than 12 % w.b. (Figs. 1 and 2). The peak values of dielectric properties at MW ranges (Figs. 1 and 2a,b) could be caused by lower ionic conduction and greater bound water relaxation. The trends are similar to the results reported by Wang et al. (2003a, b) with peak values in the range of 500–1000 MHz for walnuts and almonds. These frequency-dependent trend differences are probably caused by the low density used in Wang et al. (2003a, b), suggesting a complex interaction among frequency, temperature, moisture, density and fat content (Nelson 1996).

At moisture contents from 12–24 % w.b. (Figs. 1c, d, e and 2c, d, e), both dielectric constant and loss factor decreased steadily with increasing frequency at all five temperatures. Temperature and moisture content played important roles in the extent of the dielectric properties dependency on frequency especially within the RF range (10 to 300 MHz). Higher moisture contents and temperatures led to more pronounced depression of dielectric properties with increasing frequency from 10 to 1,800 MHz. For example, at the moisture content of 24 % w.b., dielectric constant and loss factor at 100 °C decreased from 45.5 to 15.6 and 445.9 to 5.9, respectively, as frequency changed from 10 to 1,800 MHz, compared to a decrease of 27.2 to 13.3 and 119.0 to 3.9, respectively, at 25 °C. The means and standard deviations of dielectric properties are summarized in Table 3 for macadamia nut kernels at five moisture contents, four frequencies, and five temperatures, which could be useful for computer simulation.

Similar trends are reported for grains, oil seeds, fruits, and vegetables (Berbert et al. 2002; Nelson 2003; Zhuang et al. 2007; Guo et al. 2008; Jiao et al. 2011). Electric conduction, dipole, electronic, atomic and Maxwell–Wanger polarization mechanisms contribute to the dielectric properties (Metaxas and Meredith 1983; Kuang and Nelson 1997), but ionic conduction may play a dominant effect on the magnitude of the loss factor of biological materials with high moisture contents. For example, for macadamia nut kernels with moisture content from 12 % to 24 % w.b., the loss factor at low frequencies contributed by ionic conduction was much larger than that due to dipole rotation (Fig. 2c–e) as observed by Nelson (2003); Wang et al. (2005), and Guo et al. (2008).

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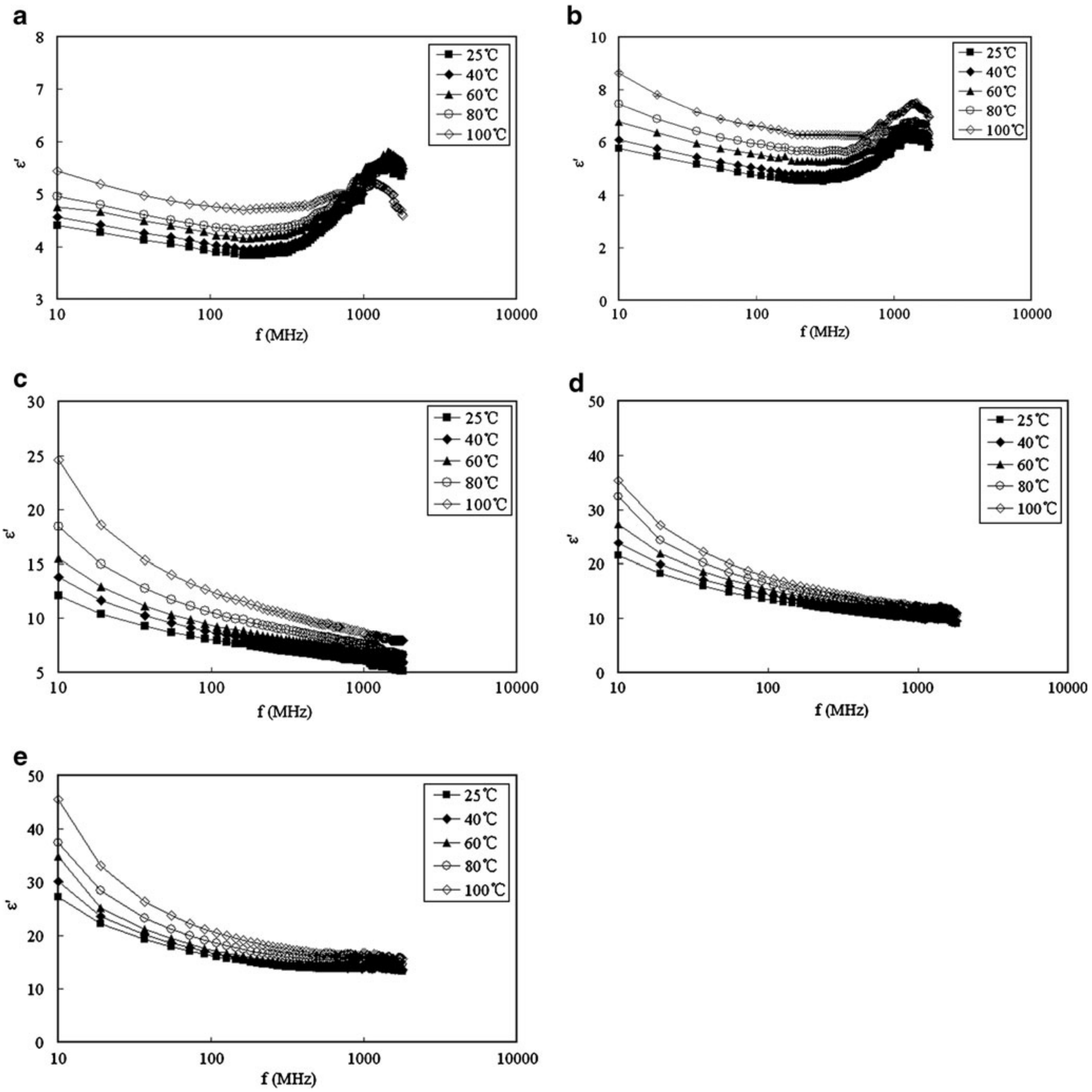

Fig. 1 Frequency-dependent dielectric constant of macadamia nut kernels at five temperatures and moisture contents of 3 % (**a**), 6 % (**b**), 12 % (**c**), 18 % (**d**) and 24 % w.b. (**e**)

Moisture-Dependent Dielectric Properties of Nut Kernels

At low moisture contents of 3 and 6 % w.b., both dielectric constant and loss factor were all very low (Table 3). This is because at those low moisture contents, most water molecules are bound to proteins or starch in the nut kernels (Singh et al. 2006). Figure 3 compares the influence of moisture contents on the dielectric properties of nut kernels at RF and MW frequencies for two temperatures. Overall, nut kernels had higher dielectric constant and loss factor values at RF frequencies when compared to those at MW frequencies. At a fixed frequency, dielectric properties of the nut samples increased with increasing moisture content. Pronounced increases in dielectric constant were observed at all four RF and MW frequencies, although more at RF ranges (Fig. 3a,b) as moisture content increased. For loss factors, the increase was very sharp at RF frequencies, but much less at the MW frequencies (Fig. 3c,d). The increase

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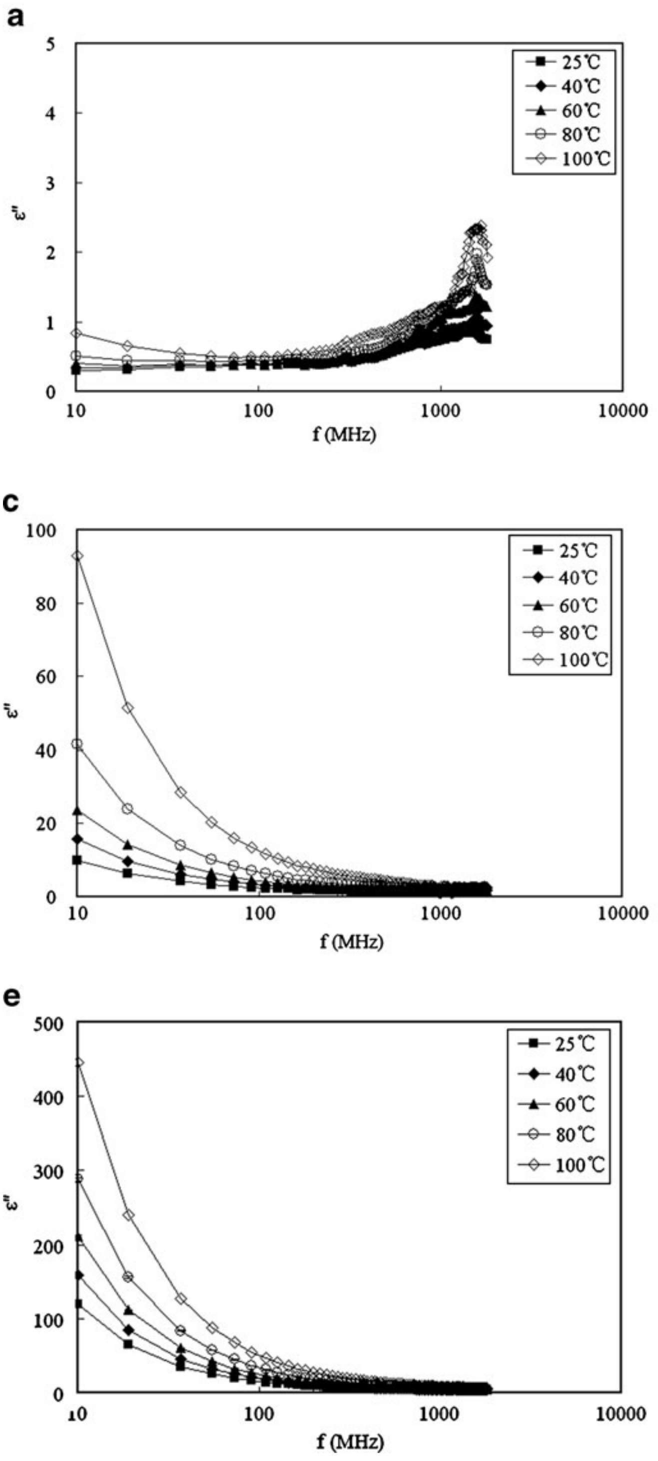

Fig. 2 Frequency-dependent dielectric loss factor of macadamia nut kernels at five temperatures and moisture contents of 3 % (**a**), 6 % (**b**), 12 % (**c**), 18 % (**d**) and 24 % w.b. (**e**)

in dielectric properties as moisture content increased from 3 to 24 % can be attributed to the transition of bound water state from monolayer or multilayer to free water. Singh et al. (2006) reported that for *Brassica compestris* oilseed, water appeared in a monolayer state when moisture content was less than 8 %. Water molecules were bound in form of multi-layers as moisture content increased from 8 to 13 % w.b. Since the ionic conductivity is the dominant polarization mechanism at low frequencies, the dielectric losses are considerably higher. These mechanisms diminish as the frequency increases (Nelson and

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Table 3 Dielectric properties (mean±SD) of macadamia nut kernels at five moisture contents, five temperatures and four frequencies

Moisture content (%, w.b.)	Frequency (MHz)	Dielectric properties	Temperature (°C)				
			25	40	60	80	100
3	27.12	ε'±SD	4.3±0.6	4.3±0.6	4.5±0.1	4.7±0.7	5.1±0.3
		ε''±SD	0.3±0.2	0.4±0.1	0.4±0.1	0.4±0.2	0.6±0.2
	40.68	ε'±SD	4.2±0.6	4.2±0.4	4.4±0.1	4.7±1.0	5.1±1.7
		ε''±SD	0.4±0.2	0.4±0.2	0.4±0.1	0.5±0.2	0.6±0.2
	915	ε'±SD	5.2±0.9	5.1±0.4	5.2±0.3	5.3±0.4	5.1±0.2
		ε''±SD	0.8±0.3	0.9±0.3	1.0±1.0	1.2±0.1	1.4±0.3
	1,800	ε'±SD	5.5±0.5	5.4±1.2	5.5±1.3	5.6±0.5	5.8±0.5
		ε''±SD	0.8±0.3	0.9±0.3	1.1±0.7	1.5±0.2	1.9±0.4
6	27.12	ε'±SD	5.3±0.2	5.6±0.2	6.1±0.02	6.6±0.3	7.4±0.2
		ε''±SD	0.8±0.2	0.9±0.1	1.2±0.2	1.7±0.4	2.9±0.3
	40.68	ε'±SD	5.1±0.2	5.4±0.3	5.9±0.3	6.4±0.2	7.1±0.2
		ε''±SD	0.7±0.2	0.8±0.3	1.1±0.2	1.4±0.2	2.3±0.3
	915	ε'±SD	5.5±0.2	5.7±0.2	5.9±0.3	6.1±0.3	6.8±0.2
		ε''±SD	1.0±0.4	1.0±0.2	1.1±0.2	1.1±0.7	1.4±0.3
	1,800	ε'±SD	5.9±0.3	6.0±1.0	6.3±0.3	6.5±0.3	7.0±0.1
		ε''±SD	1.0±0.2	1.1±0.6	1.2±0.4	1.2±0.3	1.6±0.2
12	27.12	ε'±SD	9.3±0.6	10.2±0.3	11.1±0.2	12.2±0.5	13.8±0.3
		ε''±SD	5.7±0.8	7.9±0.9	11.0±0.8	15.9±2.2	26.0±1.9
	40.68	ε'±SD	8.8±0.6	9.5±0.2	10.3±0.4	11.2±0.5	12.6±0.4
		ε''±SD	4.4±0.6	5.9±0.9	8.1±0.6	11.7±4.2	18.5±0.6
	915	ε'±SD	6.0±0.2	6.5±0.3	6.8±0.4	7.2±0.6	7.5±0.3
		ε''±SD	1.4±0.3	1.6±0.3	1.7±0.3	1.9±0.3	2.2±0.2
	1,800	ε'±SD	5.6±0.3	6.0±0.6	6.3±0.2	6.7±0.3	7.0±0.2
		ε''±SD	1.5±0.4	1.6±0.2	1.7±0.2	1.8±0.3	2.1±0.2
18	27.12	ε'±SD	16.7±0.3	18.1±0.6	19.8±0.6	21.6±0.8	24.7±0.9
		ε''±SD	22.8±2.0	30.9±3.4	42.4±3.4	57.7±6.7	94.5±8.2
	40.68	ε'±SD	15.3±0.4	16.6±0.5	18.0±0.5	19.5±0.5	21.9±0.5
		ε''±SD	16.5±1.3	22.1±2.4	30.0±2.4	40.6±4.2	65.3±4.7
	915	ε'±SD	9.5±0.2	10.0±0.3	10.6±0.2	11.1±0.3	11.7±0.3
		ε''±SD	2.7±0.1	3.0±0.2	3.4±0.1	3.9±0.3	5.1±0.2
	1,800	ε'±SD	8.4±0.4	9.1±0.2	9.6±0.4	10.1±0.3	10.6±0.3
		ε''±SD	2.4±0.2	2.5±0.6	2.7±0.2	2.9±0.2	3.6±0.4
24	27.12	ε'±SD	20.6±0.5	21.6±0.5	22.9±1.8	25.5±0.8	29.2±1.3
		ε''±SD	47.5±4.7	61.7±6.4	81.0±3.5	113.1±7.6	173.5±15.2
	40.68	ε'±SD	18.9±2.0	19.8±1.2	20.8±0.8	22.8±1.5	25.7±2.8
		ε''±SD	33.4±3.1	42.8±6.9	56.2±2.3	78.0±4.9	119.3±9.3
	915	ε'±SD	13.8±1.3	14.3±1.3	14.5±0.4	15.1±0.7	16.3±2.8
		ε''±SD	4.5±0.4	4.8±1.6	5.5±0.7	6.4±0.5	8.5±0.5
	1,800	ε'±SD	13.3±0.7	13.6±0.7	13.9±1.5	14.6±0.9	15.7±1.5
		ε''±SD	3.9±0.4	4.1±1.2	4.2±0.4	4.8±0.5	5.9±0.4

Trabelsi 2009). Viscosity of biomaterials sharply decreases with increasing temperature, thus raising ionic conductivity (Tang et al. 2002). So it can be found from Fig. 3d that at 60 °C, the loss factor of macadamia nut kernels at 27.12 MHz increased more sharply with the increase in moisture content than at 25 °C. Sacilik et al. (2007) studied dielectric properties of safflower seeds over a frequency range of 50 kHz to 10 MHz at the moisture content range of 5.06–14.15 % w.b. Similar trends are also observed in other studies (Nelson and Stetson 1976; Noh and Nelson 1989; Kim et al. 2003).

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The behavior of decreasing loss factor with reduced moisture content at RF frequencies may lead to the potentially advantageous phenomenon, commonly referred to as "moisture leveling effect" (Metaxas and Meredith 1983; Feng et al. 2002), when drying macadamia nut kernels using RF energy. In a batch RF drying process of macadamia nut kernels, the nut kernels with high moisture contents could be heated preferentially and thus more rapidly, causing more water vaporization than those with low moisture contents. As a result, in properly designed RF drying systems, the final product should have relatively uniform moisture content. Based on Fig. 3c, the moisture leveling effect should be very strong in nut kernels when dried from 24 to 6 % at 60 °C in 27.12 or 40.68 MHz RF drying systems.

Temperature-Dependent Dielectric Properties of Nut Kernels

The temperature-dependent dielectric constant and loss factor of macadamia nut kernels at different moisture contents and two frequencies (27.12 MHz representing RF and 915 MHz representing MW) are compared in Fig. 4. Increasing temperature resulted in significant increases in the dielectric constant and loss factor of macadamia kernels at a fixed frequency for moistures between 12 and 24 % w.b., especially at 27.12 MHz (Fig. 4a and c). This may be due to the predominant ionic conduction that occurs at low frequencies and high moisture contents. Little increase in the dielectric constant and loss factor was observed over the temperature range from 25 to 100 °C at moisture contents of 3 and 6 % at both 27.12 and 915 MHz. For nut kernels with moisture content of less than 6 %, there existed little ionic conduction, more bound water relaxation, and less free water dispersion. So the dielectric constant and loss factor increased little with increasing temperature even over the RF frequency range. Slight increases in dielectric properties of the nut kernels with temperature were observed at moisture contents from 3 to 24 % at MW frequencies (Fig. 4b,d). The behavior of the loss factor with temperature at RF frequencies may lead to a phenomenon referred to as "thermal run away" when drying using RF energy. That is, when products of non-uniform moisture content are dried in a RF system, the portion of the samples with high moisture content could be heated preferentially, leading to high sample temperature, thus high loss factor, which in turn causes even more RF heating. If the higher conversion of RF energy into the higher moisture portion cannot be effectively taken away by other means, product temperature could increase as more energy is absorbed due to the increase

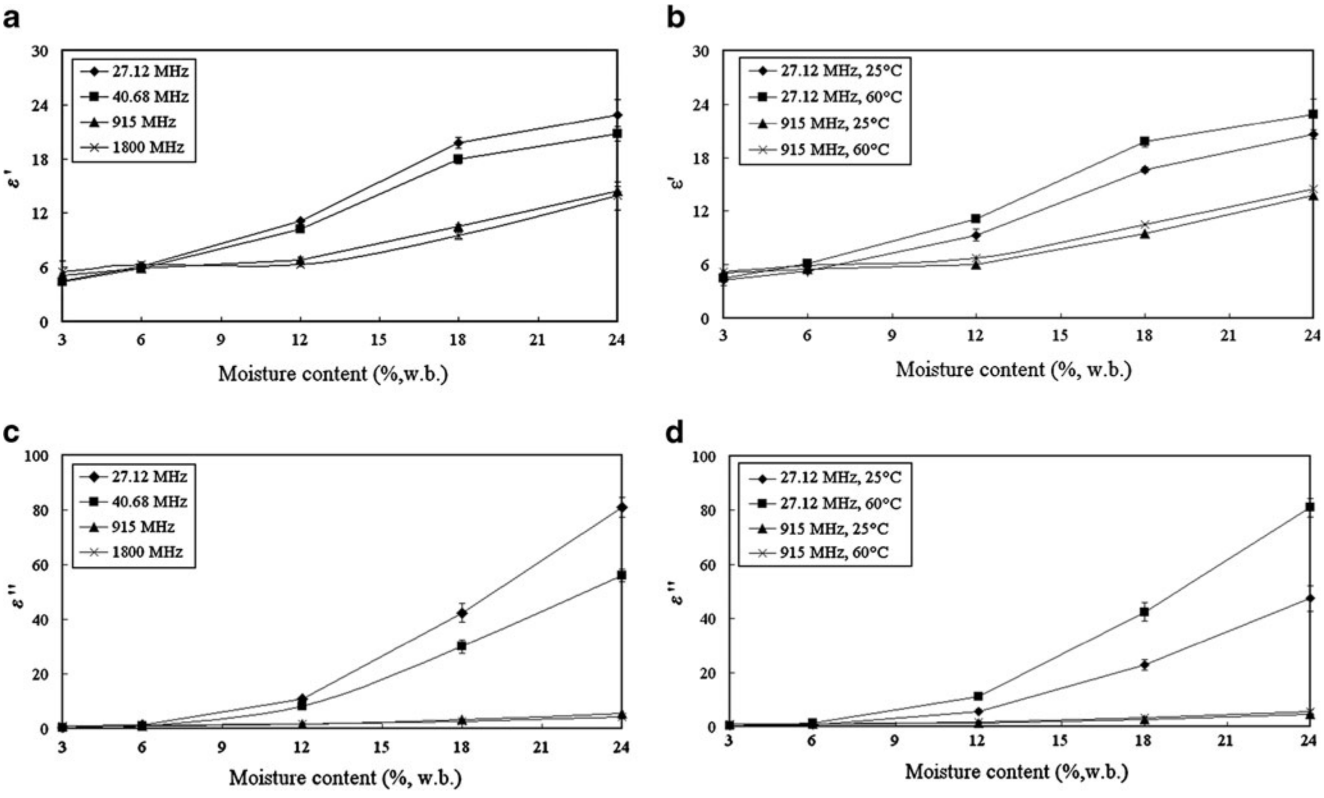

Fig. 3 Moisture-dependent dielectric properties of nut kernels for comparison at four specific frequencies at 60 °C (**a**, **c**) and at two selected frequencies and temperatures (**b**, **d**)

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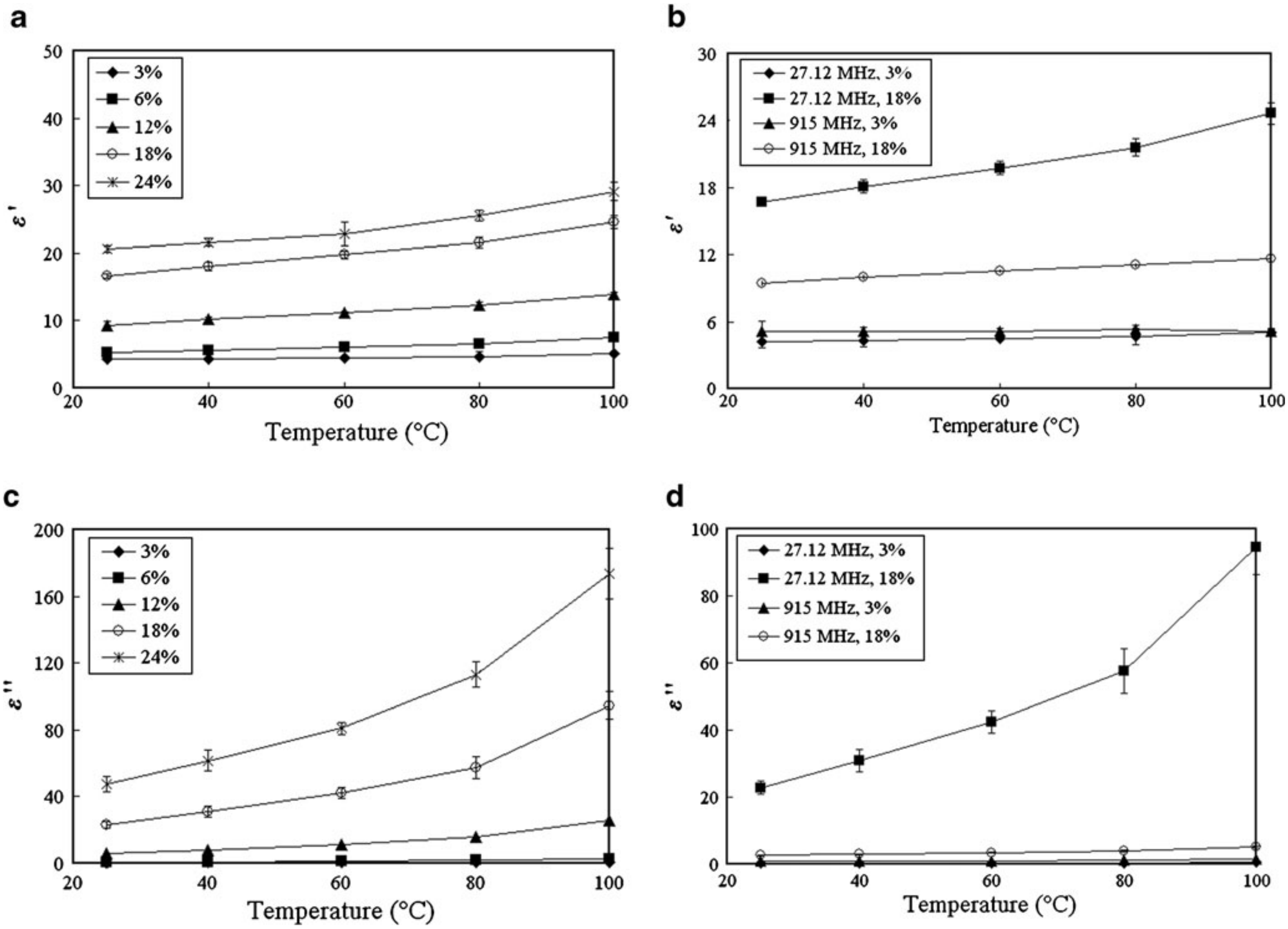

Fig. 4 Temperature-dependent dielectric properties of nut kernels for comparison at the five selected moisture contents at 27.12 MHz (**a**, **c**) and at two frequencies and two moisture contents (**b**, **d**)

in loss factor. In order to avoid this run away phenomenon in RF drying of nuts, measures should be taken to maintain an equilibrium between energy input and output. In RF drying, heat is generated throughout the product by ionic conduction and water excitation. A vapor pressure gradient would develop from the kernel inner to the shell surface. Under this pressure difference, moisture may then migrate to the material surface. To make the process smooth and efficient, surface air drying in combination with internal MW and RF heating could be an appropriate way to improve drying uniformity (Wang et al. 2011).

Penetration Depth

Penetration depths of electromagnetic waves in nut kernels at four frequencies, five moisture contents, and five temperatures are summarized in Table 4. Penetration depths at RF frequencies were much larger than those at MW frequencies for nut kernels with the same moisture contents and temperatures. Penetration depths at 27.12 MHz ranged from 1121 to 10 cm for nut kernels, depending upon the kernel moisture content and temperature. In contrast, at 915 MHz, the penetration depth for the nut kernels was much lower (from 13 to 4 cm). The penetration depth trends as influenced by moisture content and temperature are shown in Fig. 5. Penetration depths decreased sharply with moisture content and temperature at 27.12 MHz, but the degree of reduction was less at MW frequencies (Fig. 5a). Moisture content had a larger effect on penetration depths than temperature. At high moisture contents (>12 %), moisture had little effect on penetration depth. Below 12 % moisture content, RF penetration depth increased sharply with decreasing moisture. Deeper penetration would be expected at lower frequencies such as at RF compared to MW (Metaxas and Meredith 1983). Similar results are reported in several studies (Wang et al. 2003a; Guo et al. 2010; Jiao et al. 2011). Smaller penetration depth at MW frequencies in nut kernels means greater surface heating. For most foods, dielectric properties values are large due to relatively high moisture content. Thus, MW energy with the short wavelength penetrates into only shallow layers in most food

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Table 4 Calculated penetration depths (mean±SD) of electromagnetic waves in macadamia nut kernels at four frequencies, five moisture contents, and five temperatures

Moisture content (%, w.b.)	Frequency (MHz)	Penetration depth (cm)				
		Temperature (°C)				
		25	40	60	80	100
3	27.12	1121.1±130.7	1015.7±85.8	916.2±74.8	859.8±71.3	647.8±40.5
	40.68	687.3±85.5	672.5±112.5	586.6±43.2	560.4±38.6	476.3±31.6
	915	14.5±0.9	13.7±1.1	12.3±3.5	10.4±0.2	8.6±0.5
	1,800	7.7±0.6	6.6±0.4	5.7±0.8	4.1±0.1	3.4±0.1
6	27.12	523.6±27.1	471.2±5.7	356.7±14.7	266.7±14.8	167.2±4.4
	40.68	368.7±26.9	331.9±27.4	267.7±11.7	207.6±7.0	139.6±4.1
	915	12.3±1.4	12.2±0.6	11.7±0.5	11.8±2.0	9.5±0.6
	1,800	6.3±0.3	6.0±0.7	5.8±0.6	5.5±0.3	4.4±0.2
12	27.12	98.9±3.0	76.2±2.0	58.6±0.9	44.4±1.2	31.5±0.4
	40.68	82.0±2.5	64.0±2.4	49.4±0.7	37.0±3.0	26.4±0.1
	915	9.1±0.5	8.6±0.5	8.0±0.3	7.4±0.2	6.5±0.1
	1,800	4.3±0.3	4.0±0.1	3.9±0.1	3.8±0.2	3.4±0.1
18	27.12	36.5±0.7	29.6±0.6	23.9±0.4	19.7±0.4	14.6±0.2
	40.68	30.9±0.5	25.0±0.6	20.1±0.3	16.4±0.3	12.1±0.2
	915	6.1±0.1	5.6±0.1	5.1±0.1	4.5 ± 0.1	3.6±0.0
	1,800	3.3±0.1	3.2±0.2	3.0±0.0	2.9±0.0	2.4±0.1
24	27.12	22.3±0.4	18.8±0.4	15.9±0.1	13.1±0.1	10.3±0.1
	40.68	18.8±0.5	15.9±0.1	13.3±0.1	10.9±0.1	8.5±0.1
	915	4.4±0.1	4.1±0.3	3.7±0.1	3.2±0.1	2.6±0.0
	1,800	2.5±0.0	2.4±0.0	2.4±0.0	2.1±0.0	1.8±0.0

products. But RF heating with higher penetration depths would result in more uniform electric fields in the bulk mass of nut kernels, thus improve heating uniformity, which is one of the most important advantages of RF drying compared with MW heating.

Conclusions

Dielectric properties data for macadamia kernels were studied at four frequencies, five moisture contents, and five temperatures. Dielectric constant and loss factor of nut

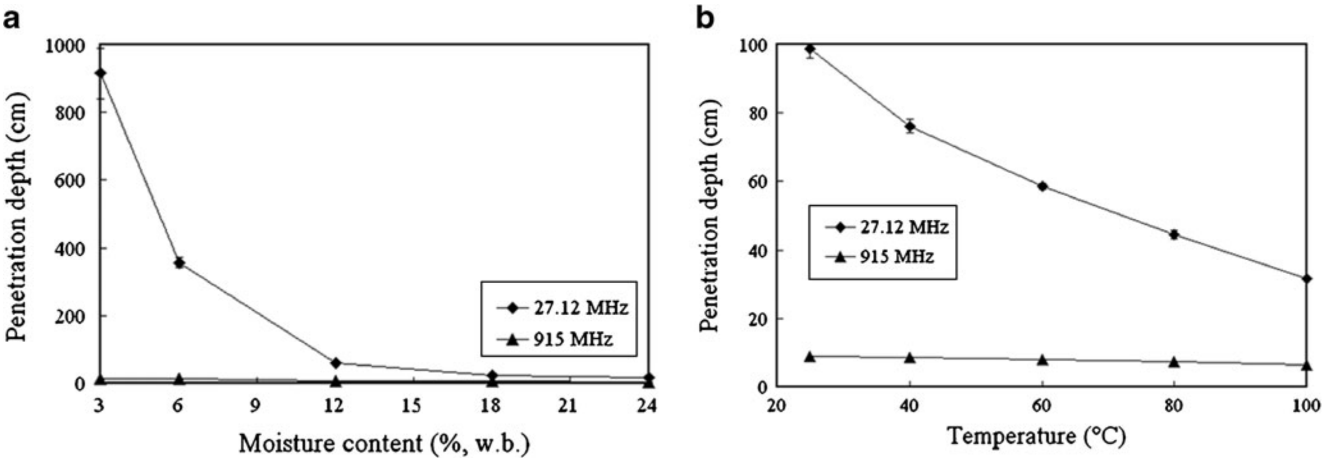

Fig. 5 Penetration depth of electromagnetic waves in nut kernels at two frequencies as influenced by moisture content at 60 °C (**a**) and temperature for kernel samples at 12 % w.b. (**b**)

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kernels decreased sharply with increasing frequency in the tested RF range, whereas more gradually in the tested MW range. Low values and slight increase in dielectric properties were observed in samples with moisture content from 3 to 6 % and attributed to strongly bound water, which could limit water molecular polarization. The increase of loss factor with moisture content at RF frequencies may lead to "moisture leveling effect", when drying macadamia kernels using RF energy. Increasing temperature resulted in significant increases in dielectric properties at moisture contents from 6 to 24 %, especially in the RF range. The increase of loss factor with moisture content and temperature at RF frequencies may lead to the phenomenon referred to as "thermal run away". Higher penetration depths at RF frequencies might result in a relatively more uniform heating in drying thick layers of macadamia nuts.

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