DIELECTRIC PROPERTIES OF GROUND HAZELNUTS AT DIFFERENT FREQUENCIES, TEMPERATURES, AND MOISTURE CONTENTS

X. Zhu, W. Guo, S. Wang

ABSTRACT. *To develop advanced drying methods using microwave or radio frequency energy, the dielectric constant (ε′) and loss factor (ε″) of ground hazelnuts at moisture contents between 4.6% and 20.3% wet basis (w.b.) were determined from 10 to 4500 MHz at 20°C to 60°C using an open-ended coaxial probe and a network analyzer. The results showed that both ε′ and ε″ decreased with increasing frequency but increased with increasing moisture content and temperature. Both ε′ and ε″ decreased more at the low frequency end of the range than at the high frequency end, especially for high moisture levels. They increased almost linearly with increasing temperature. Third-order polynomial models could be used to describe ε′ and ε″ as functions of moisture content and temperature at selected frequencies. Each model provided a good fit to the experimental data at a significance level of 0.0001 and with a coefficient of determination greater than 0.990. The power penetration depth decreased with increasing frequency, moisture content, and temperature. Large penetration depths at frequencies below 100 MHz may provide large-scale drying.*

Keywords. *Dielectric constant, Dielectric loss factor, Hazelnut, Moisture content, Temperature.*

Hazelnut is one of the most nutrient-rich and healthful nuts (Monagas et al., 2009). It is consumed all over the world as a dried fruit and as an additive to a diversity of manufactured food products, including snacks, chocolates, cereals, ice creams, and other dessert formulations (Seyhan et al., 2007). Hot-air drying of shelled hazelnut kernels to a moisture content of about 4% to 5% wet basis (w.b.) is the main process in manufacturing hazelnut flour. However, long processing time, high energy consumption, and low heating efficiency are its main disadvantages. For example, when fresh hazelnuts were heated at 40°C and 0.38 m s^{-1} and at 50°C and 0.26 m s^{-1}, 30 h and 24 h were needed to reduce the initial moisture content of 27.0% w.b. to 5.4% and 3.8% w.b., respectively (Ceylan and Aktaş, 2008). Although increased temperature was helpful in removing moisture from hazelnut (Topuz et al., 2004), high temperature might degrade the overall product quality. Moreover, at the beginning of traditional drying, the drying rate was high due to the high surface moisture content, but the drying rate decreased as the central moisture in the sample approached evaporation (Topuz et al., 2004).

In contrast to conventional heating mechanisms (i.e., convection or conduction), in which heat is usually transferred from the surface to the interior, dielectric heating allows volumetric heating whereby heat is transferred to the inner core of a material without the need of a temperature gradient, even in the initial stage of drying. Dielectric drying results in a high heating rate, short processing time, and good heating uniformity (Coronel et al., 2003; Salazar-González et al., 2012; Zhu et al., 2007; Campañone et al., 2012; Mujumdar and Law, 2010). Several studies have demonstrated that radio frequency or microwave heating, either alone or combined with conventional methods, offer advantages that cannot be obtained with traditional heating techniques (Zielinska et al., 2013; Akbudak and Akbudak, 2013; Wang et al., 2013; Albanese et al., 2013). The effects of microwave treatment at 2450 MHz on hazelnut showed that the taste and odor of hazelnut treated with microwave heating was unaffected during storage (Basaran and Akhan, 2010).

Dielectric properties are the main parameters that provide information about how materials interact with electromagnetic energy during dielectric heating. They are critical to develop effective radio frequency or microwave treatment 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). The dielectric properties of most interest are the relative dielectric constant (ε′) and the relative dielectric loss factor (ε″), which are the real and imaginary parts, respectively, of the relative complex permittivity (ε*, where $\varepsilon^* = \varepsilon' - j\varepsilon''$). Dielectric property data have been reported for several dried fruits, such as raisins, dates, apricots, figs, and prunes (Alfaifi et al., 2013), walnuts (Wang et al., 2003), chestnuts (Guo et al., 2011; Zhu et al.,

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2012b), and peanuts (Boldor et al., 2004). These studies show that frequency, moisture content, and temperature are important factors affecting the dielectric properties of nut materials.

Fundamental understanding of the dielectric properties of hazelnut is essential for developing drying protocols and determining treatment bed depth for drying hazelnut with radio frequency or microwave energy. The aims of this study were to (1) determine the dielectric properties of ground hazelnut in the frequency range of 10 to 4500 MHz, moisture content range of 4.6% to 20.3% w.b., and temperature range of 20°C to 60°C; (2) establish mathematic models describing ground hazelnut's dielectric properties as functions of moisture content and temperature at the frequencies of interest; (3) estimate the penetration depth of electromagnetic waves in hazelnut; and (4) investigate the feasibility of drying hazelnut with radio frequency or microwave heating.

MATERIALS AND METHODS

MATERIALS AND SAMPLE PREPARATION

Freshly harvested in-shell hazelnuts, variety Liaozhen No. 1, supplied by a hazelnut farmer in Tieling, Liaoning, China, were used in this study. The samples were cracked manually for collection of hazelnut kernels without shells and pellicles. The original moisture content of the fresh hazelnut kernels was 24.2% ±0.3% w.b. Since close contact is needed between the coaxial probe surface and the material in measuring dielectric properties, about 15 kg of fresh hazelnut kernels were dried at 40°C in a forced-air oven (WG-71, Tianjin Taisite Instrument Co., Ltd., Tianjin, China) until they were dehydrated to about 4% w.b., followed by grinding in a laboratory grinder. The initial moisture content of the ground hazelnut samples was 4.6% ±0.2% w.b., and samples of 80 mesh fineness were used. To obtain samples with different moisture levels, four sublots of about 250 g at a moisture content of 4.6% w.b. were placed in polyethylene bags. Predetermined amounts of deionized water were added to these samples by spraying them several times. The bags were sealed, shaken, stored at 4°C for 3 to 6 days, and shaken 3 to 5 times every day to allow uniform moisture distribution throughout the samples. About 2 to 3 g of ground hazelnut at each moisture content were dried at 130°C for 1 h to determine the moisture content with three replicates (AOAC, 1998). Five moisture levels were obtained: 4.6% ±0.1%, 8.4% ±0.1%, 12.2% ±0.1%, 15.5% ±0.2%, and 20.3% ±0.3% w.b.

Preliminarily experiments showed that when the moisture content of hazelnut kernels was between 4.2% and 18.6% w.b., the kernel density was within 0.993 to 1.022 g cm^{-3}. Since the change in kernel density with moisture content was small, the density of the hazelnut kernels was not considered in this study.

DIELECTRIC PROPERTIES MEASUREMENT SYSTEM

The system used to measure dielectric properties consisted of an E5071C vector network analyzer, a 85070B open-ended coaxial probe, 85070 dielectric probe kit software (Agilent Technologies, Penang, Malaysia), a computer, a constant-temperature water bath (DK-98-1, Tianjin Taisite Instrument Co., Ltd., Tianjin, China), a hydraulic platform, a temperature meter, and a stainless steel cylindrical sample holder (23 mm in diameter and 25 mm in height) welded onto a stainless steel plate and custom-built for use with the 85070B probe. The measurement system is shown in figure 1.

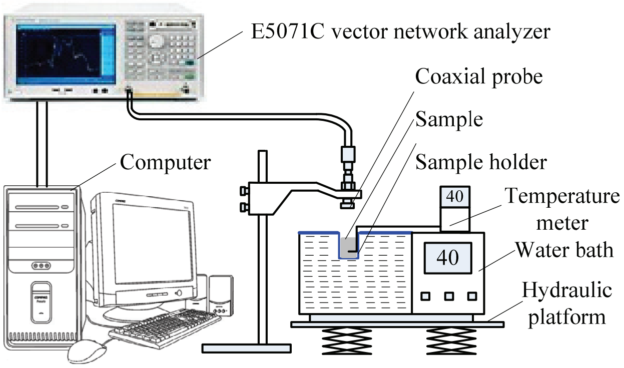


Figure 1. Dielectric properties measurement system.

MEASUREMENT PROCEDURE

After the network analyzer was powered on for at least 1 h, it was calibrated with open circuit, short circuit, and 50 Ω load at one port. The calibrated port was connected to the 85070B probe with a low-loss coaxial cable. Settings were made to provide measurements at 51 frequencies on a logarithmic scale from 10 to 4500 MHz. The 85070B probe was calibrated with air, short circuit, and 25°C deionized water. The measurement on 25°C deionized water was done to verify that accurate permittivity values were obtained; if not, the probe was calibrated again.

About 10 g of ground hazelnut was placed in the stainless steel cylindrical sample holder. The stainless steel plate with the sample holder was placed in the constant-temperature water bath so that the holder was submerged in water. The temperature meter was used to detect the sample temperature. The water bath was elevated by the hydraulic platform to bring the ground hazelnut sample into good contact with the 85070B probe (with 18.96 mm diameter ground plane flange). The sample temperature was controlled by the circulating water in the water bath, and the water temperature was set at 20°C, 30°C, 40°C, 50°C, and 60°C in sequence. After the sample temperature reached the set value, measurements of dielectric properties were conducted three times at 51 discrete frequencies from 10 to 4500 MHz. All measurements were repeated in triplicate. Mean values and standard deviations of permittivities were calculated from nine readings.

SOFTWARE AND METHODOLOGY FOR POLYNOMIAL FITTING

Permittivity data of ground hazelnut at selected frequencies were analyzed using Design-Expert 7.1.6 (Stat-Ease, Inc., Minneapolis, Minn.) to develop mathematical models describing the relationship between permittivities (ε' and ε'') and moisture content and temperature. The moisture content and temperature were used as factors, the ε′ and ε″ values obtained at selected frequencies were used as response variables, central composite was used as the design method, and analysis of variance (ANOVA) was used to evaluate the significance of each variable on the regression models.

POWER DISSIPATION AND PENETRATION DEPTH

The power dissipated per unit volume (P, W m^{-3}) in a nonmagnetic and uniform material exposed to a radio frequency or microwave electric field can be expressed as (Datta and Anantheswaran, 2001):

$$P = 55.63 \times 10^{-12} fE^2 \varepsilon'' \tag{1}$$

where E is the electric field intensity (V m^{-1}), f is the frequency of the electric field (Hz), and ε″ is the dielectric loss factor of the material to be heated in the electric field.

Penetration depth is an important parameter in evaluating heating uniformity and in deciding the thickness of samples to be treated during radio frequency or microwave heating. The penetration depth (d_p, m) for radio frequency and microwave energy in a lossy food material can be calculated as (Metaxas and Meredith, 1983):

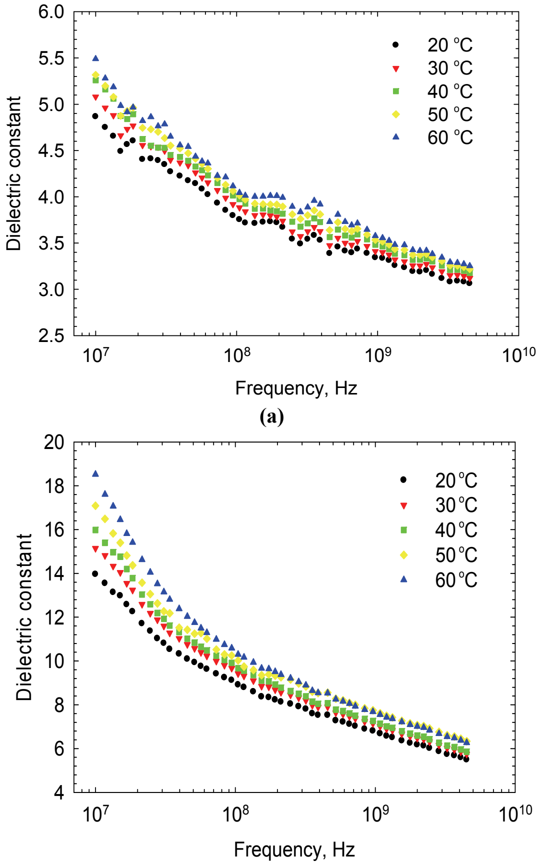
$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right]}} \tag{2}$$

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

RESULTS AND DISCUSSION

FREQUENCY DEPENDENCE OF DIELECTRIC CONSTANT

The mean ε′ values of ground hazelnut samples obtained at moisture contents of 8.4% and 12.2% w.b. at five temperatures from 10 to 4500 MHz are shown in figure 2, which indicates that ε′ decreased with increasing frequency over the investigated frequency range. For samples at 20°C with moisture contents of 8.4% and 12.2%, ε′ decreased from 4.86 and 13.95 at 10 MHz to 3.02 and 5.49 at 4500 MHz, respectively. It was found that the decrease rate of ε″ increased with increasing moisture content. For example, at 20°C and with moisture contents of 4.6%, 8.4%, 12.2%, 15.5%, and 20.3% w.b., when the frequency increased from 10 to 4500 MHz, ε′ decreased by 16.4%, 37.9%, 60.6%, 65.9%, and 68.0%, respectively. Moreover, the decrease was faster at the low-frequency end of the range than at the high-frequency end, especially for higher moistures. The dielectric properties of food materials depend on the free and bound water contents in the material (Calay et al., 1994). For ground hazelnut at 4.6% moisture content, the water was mainly in bound form. The dielectric polarization attributable to bound water is much less than that of free water. As the moisture content increased, the dielectric polarization increased. Therefore, ε′ increased with moisture content at a given frequency, and the frequency dependence of ε′ was more obvious at higher moisture than at lower moisture. The increased ε′ of hazelnut samples with an increase in temperature at a given frequency can also be seen in figure 2. The increased temperature improved ionic mobility, which resulted in increased ε′.



(a)

(b)

Figure 2. Mean dielectric constant (ε′) of ground hazelnut samples at moisture contents of (a) 8.4% and (b) 12.2% w.b. at indicated temperatures over the frequency range from 10 to 4500 MHz.

MOISTURE AND TEMPERATURE DEPENDENCE OF DIELECTRIC CONSTANT

The obtained mean ε′ values of ground hazelnut samples as a function of moisture content at 20°C and selected frequencies are shown in figure 3, which illustrates that ε′ increased with increasing moisture content. A rapid increase was observed at moisture contents higher than 8.4% w.b.

Figure 4 shows the obtained mean values of ε′ as a function of temperature at 915 MHz and five moisture levels. At each moisture level, ε′ increased with increasing temperature. The increase was more obvious at higher moisture contents. For example, for samples at 8.4% and 20.3% w.b., when the temperature increased from 20°C to 60°C, ε′ increased from 3.34 to 3.57 and from 9.04 to 12.45, i.e., increases of 6.9% and 37.7%, respectively. The increase in ε′ with temperature was also found at other frequencies between 10 and 4500 MHz. The trend matched well with the results reported for other dried fruits, such as raisin, date, apricot, fig, and prune between 10 and 1800 MHz at 20°C to 60°C (Alfaifi et al., 2013), and for chestnut between 10 and 4500 MHz at 20°C to 60°C (Zhu et al., 2012b; Guo et

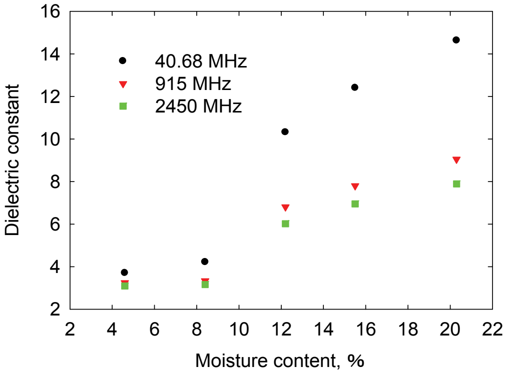


Figure 3. Mean dielectric constant (ε′) of ground hazelnut samples as a function of moisture content at three frequencies and 20°C.

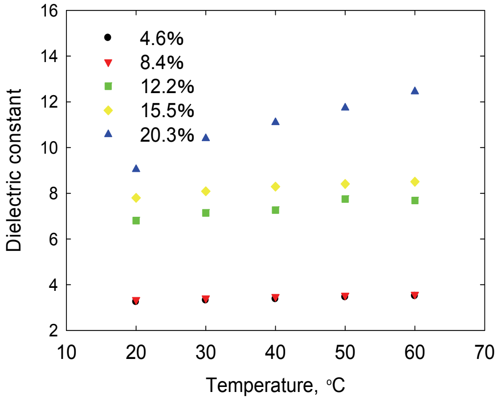


Figure 4. Mean dielectric constant (ε′) of ground hazelnut samples as a function of temperature at 915 MHz and five moisture levels.

al., 2011).

To better understand the relationship between dielectric constant, moisture content, and temperature, the obtained ε′ values of ground hazelnut at 40.68 MHz are plotted as functions of moisture content and temperature over a moisture range from 4.6% to 20.3% w.b. and a temperature range from 20°C to 60°C in figure 5. Obviously, ε′ increased with increasing moisture content and temperature. Similar moisture and temperature dependent ε′ values were found at other frequencies. Their relationship at the frequencies of interest, i.e., 27.12, 40.68, 915, and 2450 MHz, were analyzed using Design-Expert 7.1.6. The regressed polynomial models are given in equations 3 to 6, respectively:

$$\begin{aligned}\varepsilon'_{27.12} = {} & -62.28 + 13.63W + 0.18T - 7.84\times10^{-3}WT \\ & - 0.86W^2 - 4.07\times10^{-3}T^2 + 1.04\times10^{-3}W^2T \\ & - 9.33\times10^{-5}WT^2 + 1.78\times10^{-2}W^3 \\ & + 4.16\times10^{-5}T^3\end{aligned} \tag{3}$$

$$\begin{aligned}\varepsilon'_{40.68} = {} & -60.16 + 13.18W + 0.23T - 1.21\times10^{-2}WT \\ & - 0.84W^2 - 4.55\times10^{-3}T^2 + 1.13\times10^{-3}W^2T \\ & - 9.16\times10^{-5}WT^2 + 1.74\times10^{-2}W^3 \\ & + 4.49\times10^{-5}T^3\end{aligned} \tag{4}$$

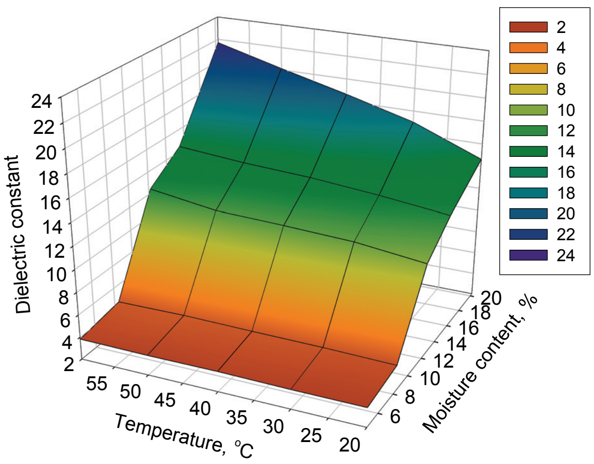


Figure 5. Dielectric constant (ε′) of ground hazelnut samples as a function of moisture content and temperature at 40.68 MHz at moisture contents of 4.6% to 20.3% and temperatures of 20°C to 60°C.

$$\begin{aligned}\varepsilon'_{915} = {} & -37.17 + 8.64W + 6.74\times10^{-2}T - 7.38\times10^{-3}WT \\ & - 0.56W^2 - 5.26\times10^{-4}T^2 + 6.61\times10^{-4}W^2T \\ & - 7.25\times10^{-5}WT^2 + 1.19\times10^{-2}W^3 \\ & + 9.43\times10^{-6}T^3\end{aligned} \tag{5}$$

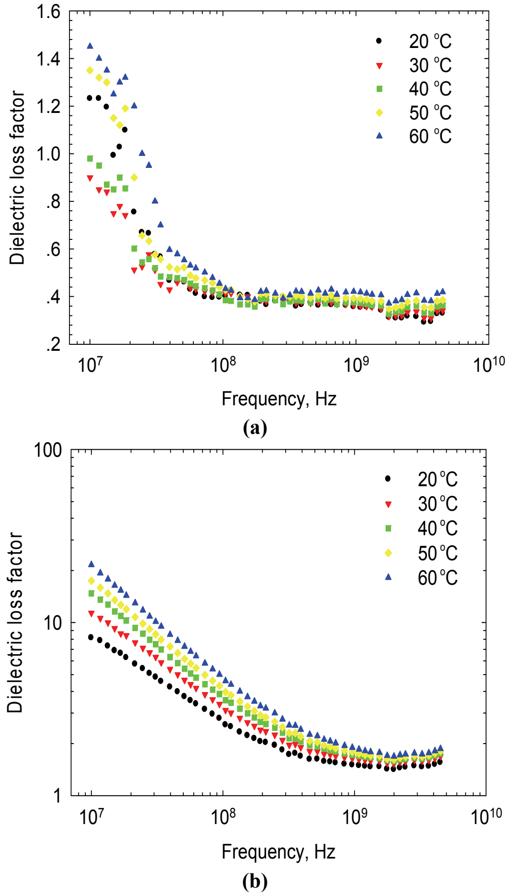
$$\begin{aligned}\varepsilon'_{2450} = {} & -28.71 + 6.70W + 5.24\times10^{-2}T - 7.46\times10^{-3}WT \\ & - 0.43W^2 - 1.21\times10^{-4}T^2 + 5.66\times10^{-4}W^2T \\ & - 4.40\times10^{-5}WT^2 + 8.96\times10^{-3}W^3 + 3.59 \\ & \times10^{-6}T^3\end{aligned} \tag{6}$$

where $\varepsilon'_{27.12}$, $\varepsilon'_{40.68}$, ε'_{915}, and ε'_{2450} are the dielectric constants of ground hazelnut samples at 27.12, 40.68, 915, and 2450 MHz, respectively, W is the moisture content ($4.6\% \le W \le 20.3\%$ w.b.), and T is the temperature ($20°C \le T \le 60°C$).

ANOVA showed that moisture content and temperature both had significant effects on dielectric constant at the 0.0001 significance level. Moreover, each model provided a good fit to the experimental data at the 0.0001 significance level with a coefficient of determination greater than 0.990.

FREQUENCY DEPENDENCE OF LOSS FACTOR

Figure 6 presents the frequency dependence of the dielectric loss factor (ε″) of ground hazelnut samples with moisture contents of 8.4% and 12.2% w.b. at five temperatures from 10 to 4500 MHz. Figure 6a indicates although ε″ decreased with increasing frequency, there were much noise for samples at 8.4% w.b. moisture, especially below 30 MHz. For samples at 12.2% w.b. moisture (fig. 6b), the ε″ values formed a “V” shape in the detected frequency range. The smallest ε″ values were at about 1100 MHz. Moreover, there were negative linear relationships between ε″ and frequency in the log-log plot from 10 to about 100 MHz (fig. 6b). Negative linear relationships were also found for other samples whose moisture content was higher than 12.2% w.b. At radio frequencies below 300 MHz and microwave frequencies, ionic conduction and dipole relaxation are the dominant loss mechanisms for foods and agri-



(a)

(b)

Figure 6. Mean dielectric loss factor (ε″) of ground hazelnut samples at moisture contents of (a) 8.4% and (b) 12.2% w.b. and indicated temperatures over the frequency range from 10 to 4500 MHz.

cultural products with high moisture contents (Ryynänen, 1995). Studies of the dielectric properties of milk, egg, and fruit juice demonstrated that the negative linear relationships between ε″ and frequency in log-log plots were caused by ionic conduction (Guo et al., 2010; Zhu et al., 2012a; Wang et al., 2009), and ionic conduction is the main loss mechanism in the lower radio frequency range. At microwave frequencies, dipole polarization is the main loss mechanism.

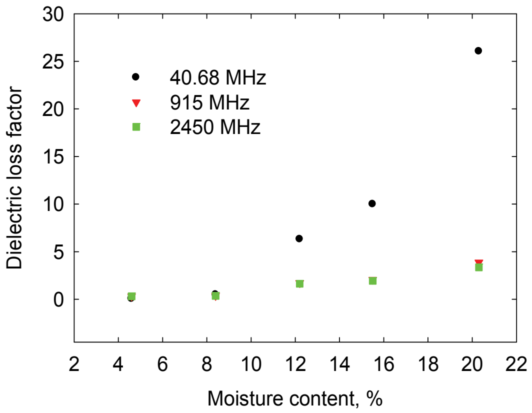


Figure 7. Mean dielectric loss factor (ε″) of ground hazelnut samples at 40.68, 915, and 2450 MHz at moisture contents of 4.6% to 20.3%.

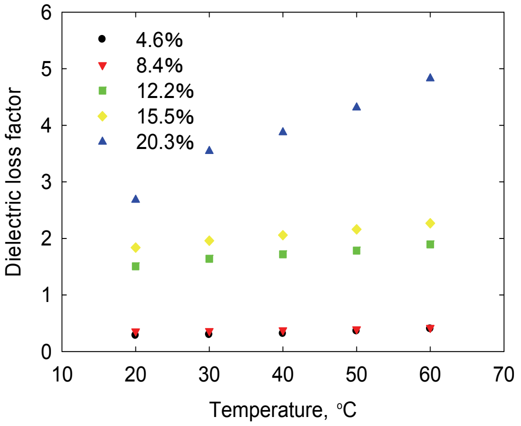


Figure 8. Mean dielectric loss factor (ε″) of ground hazelnut samples as a function of temperature from 20°C to 60°C at 915 MHz and five moisture levels.

MOISTURE AND TEMPERATURE DEPENDENCE OF DIELECTRIC LOSS FACTOR

Figure 7 shows that ε″ increased with an increase in moisture content. Below 8.4% w.b., the increase was very small, but it was obvious above 8.4% w.b., especially at 40.68 MHz. Moreover, for samples at more than 8.4% w.b. moisture, ε″ was much higher at 40.68 MHz than at 915 and 2450 MHz. This may be due to the predominant ionic conduction that occurs at low frequencies and high moisture contents. As hazelnut moisture content decreases due to the drying effect of radio frequency or microwave heating, ε″ also decreases. As a result, the higher-moisture parts absorb more energy than the lower-moisture parts, which is beneficial for uniform heating.

The loss factor increased almost linearly with increasing temperature at a given moisture content (fig. 8). The slope was greater at higher moisture contents than at lower moisture contents. For example, the slope was 0.19 at 15.5% w.b., but it increased to 0.44 at 20.3% w.b. Similar increases in ε″ with temperature were found for other ground hazelnut samples. The viscosity of biomaterials decreases with increasing temperature, thus raising the ionic conductivity (Tang et al., 2002). Consequently, temperature increases ε″. Equation 1 shows that the power dissipated per unit volume in a nonmagnetic and uniform material exposed to a radio frequency or microwave electric field has a positive linear relationship with ε″. Hazelnut may experience thermal runaway in radio frequency or microwave heating, where a rise in temperature leads to higher ε″, which in turn increases the heating rate, further increasing the temperature difference in the product. Therefore, reducing non-uniform heating is very important in drying hazelnut with radio frequency or microwave energy.

The moisture and temperature dependence of the loss factor of ground hazelnut samples at 40.68 MHz over the moisture content range from 4.6% to 20.3% and temperature range from 20°C to 60°C is graphed in figure 9, which shows that the ε″ value of ground hazelnut increased with increases in either moisture content or temperature. Similar moisture and temperature dependent values of ε″ were found for other frequencies between 10 and 4500 MHz.

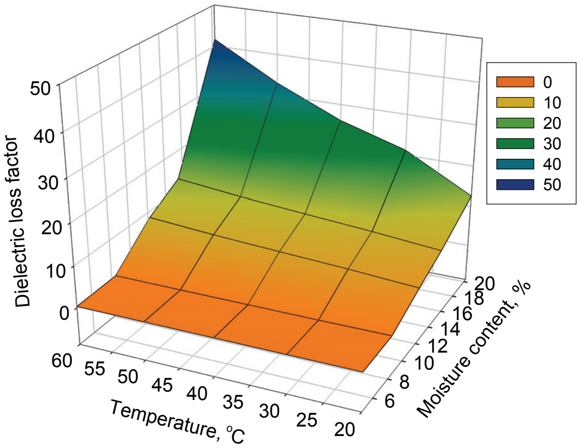


Figure 9. Dielectric loss factor (ε″) of ground hazelnut samples as a function of moisture content and temperature at 40.68 MHz at moisture contents of 4.6% to 20.3% and temperatures of 20°C to 60°C.

The polynomial regression models describing the relationship between loss factor, moisture content, and temperature at 27.12, 40.68, 915, and 2450 MHz are as follows:

$$\begin{aligned}\varepsilon''_{27.12} = {} & -135.12 + 27.81W + 1.89T - 0.192WT \\ & -1.88W^2 - 2.42\times10^{-2}T^2 + 9.01\times10^{-3}W^2T \\ & +1.97\times10^{-4}WT^2 + 4.02\times10^{-2}W^3 \\ & +1.86\times10^{-4}T^3\end{aligned} \tag{7}$$

$$\begin{aligned}\varepsilon''_{40.68} = {} & -99.82 + 20.56W + 1.33T - 0.136WT \\ & -1.39W^2 - 1.72\times10^{-2}T^2 + 6.37\times10^{-3}W^2T \\ & +1.09\times10^{-4}WT^2 + 2.98\times10^{-2}W^3 \\ & +1.35\times10^{-4}T^3\end{aligned} \tag{8}$$

$$\begin{aligned}\varepsilon''_{915} = {} & -17.23 + 3.77W + 8.58\times10^{-2}T - 6.29\times10^{-3}WT \\ & -0.26W^2 - 1.47\times10^{-3}T^2 + 4.55\times10^{-4}W^2T \\ & -3.59\times10^{-5}WT^2 + 5.67\times10^{-3}W^3 \\ & +1.55\times10^{-5}T^3\end{aligned} \tag{9}$$

$$\begin{aligned}\varepsilon''_{2450} = {} & -14.83 + 3.24W + 4.84\times10^{-2}T - 2.29\times10^{-3}WT \\ & -0.20W^2 - 9.42\times10^{-4}T^2 + 2.89\times10^{-4}W^2T \\ & -4.81\times10^{-5}WT^2 + 4.82\times10^{-3}W^3 \\ & +1.20\times10^{-5}T^3\end{aligned} \tag{10}$$

where $\varepsilon''_{27.12}$, $\varepsilon''_{40.68}$, ε''_{915}, and ε''_{2450} are the dielectric loss factor of ground hazelnut samples at 27.12, 40.68, 915, and 2450 MHz, respectively.

ANOVA showed that both moisture and temperature had significant influence on these models at the 0.0001 significance level. Each model was significant at the 0.0001 level and had a coefficient of determination higher than 0.990.

POWER PENETRATION DEPTH

The power penetration depths calculated from the measured dielectric properties of ground hazelnut samples with 15.5% w.b. at five temperatures from 10 to 4500 MHz are shown in figure 10. At a fixed temperature, the depth decreased with increasing frequency. It is evident that the penetration depth at lower frequencies was much greater than at higher frequencies. For all samples, the penetration depth at 40.68 MHz was 4 to 20 times greater than that at 915 MHz. This means that radio frequencies of 27.12 and 40.68 MHz can be used in large-scale treatments, while microwave frequencies of 915 and 2450 MHz can be used in small-scale treatments for drying hazelnut with dielectric heating. Figure 10 also shows that temperature decreased the penetration depth. At 40.68 MHz, the depth was 612 mm at 20°C and decreased to 382 mm at 60°C, a decrease of 62.4%. At 915 MHz, the penetration depth decreased from 76 to 64 mm.

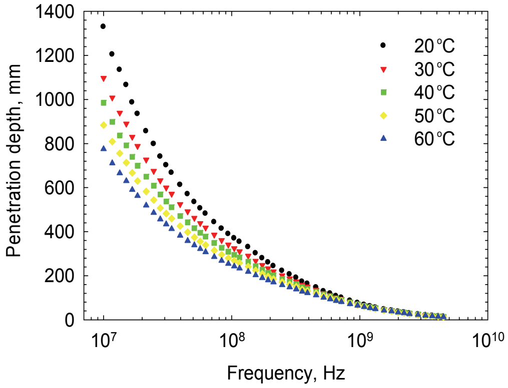


Figure 10. Calculated penetration depths from measured permittivities of ground hazelnut samples at 15.5% w.b. and five temperature levels at frequencies of 10 to 4500 MHz.

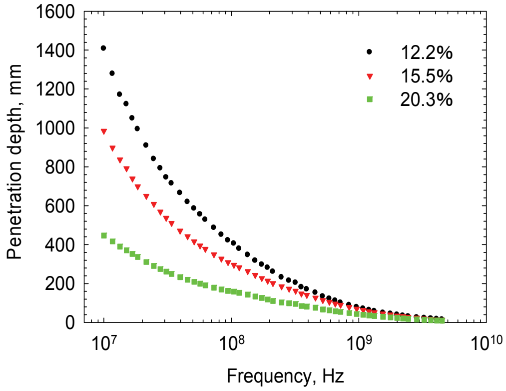


Figure 11. Calculated penetration depths from measured permittivities of ground hazelnut samples at 40°C and three moisture levels at frequencies of 10 to 4500 MHz.

Figure 11 shows the calculated penetration depths at 40°C and three moisture levels from 10 to 4500 MHz. It is evident that the penetration depth was less at the higher moisture content than at the lower moisture content. For example, at 40°C, the depth was 931 mm at 12.2% w.b. and 394 mm at 20.3% w.b., a decrease of 57.7%. Generally, the penetration depth decreased with increasing frequency, moisture content, and temperature.

CONCLUSIONS

Measurements of the permittivities of ground hazelnut samples at moisture contents from 4.6% to 20.3% w.b. and from 20 to 4500 MHz at 20°C to 60°C revealed that the permittivities of ground hazelnut were dependent on frequency, moisture content, and temperature. Both ε′ and ε″

decreased with increasing frequency and decreasing moisture content and temperature over the investigated ranges. Especially at higher moisture contents, ε′ and ε″ decreased more at the low-frequency end of the range than at the high-frequency end. They increased almost linearly with increasing temperature. Below 8.4% w.b., ε′ and ε″ increased a little with an increase in moisture content and increased quickly above 8.4% w.b. At the frequencies of interest (27.12, 40.68, 915, and 2450 MHz), the relationships between permittivities, moisture content, and temperature can be described by third-order polynomial models. Each model provided a good fit to the experimental data at the 0.0001 significance level with a coefficient of determination greater than 0.990. The power penetration depth decreased with increasing frequency, moisture content, and temperature. Radio frequency energy at 40.68 MHz had a 4 to 20 times greater penetration depth in hazelnut compared to microwave energy at 915 MHz at same moisture content and temperature. Radio frequencies below 100 MHz and microwave frequencies can be used in large-scale treatment and small-scale treatment, respectively, for hazelnut drying with dielectric heating. This research offers useful information on the dielectric properties of hazelnut related to drying with radio frequency or microwave heating.

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