Journal of Food Engineering 113 (2012) 143–150

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

# Dielectric properties of chestnut flour relevant to drying with radio-frequency and microwave energy

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ARTICLE INFO

*Article history:*
Received 10 January 2012
Received in revised form 21 April 2012
Accepted 23 April 2012
Available online 23 May 2012

*Keywords:*
Chestnut
Dielectric properties
Dielectric constant
Dielectric loss factor
Drying
Moisture content
Temperature

ABSTRACT

Dielectric properties of compressed chestnut flour samples with 11.6–48.0% w.b. moisture content were determined with a network analyzer and an open-ended coaxial-line probe over a frequency range from 10 to 4500 MHz and a temperature range from 20 to 60 °C. The results showed that the permittivities of chestnut flour were a function of frequency, moisture content and temperature. Both dielectric constant and loss factor decreased with increasing frequency but increased with increasing moisture content and temperature. The relationship between permittivities and moisture content and temperature at 27, 40, 915 and 2450 MHz could be described by second- or third-degree polynomial models, with the coefficients of determination higher than 0.993. The analysis of variance showed that moisture content and temperature had strong significant effects on permittivity values. The penetration depth decreased with increasing frequency, moisture content and temperature. Large penetration depth at radio frequencies below 100 MHz may provide practical large-scale dielectric drying of chestnut.



## 1. Introduction

Chestnut is a popular nut in the oriental world, in which China is the main producer of chestnut. Especially with carrying out the policy of returning land to forestry, the economic forestry land area increases quickly in China. Since 2009, Chinese annual output of chestnut has increased by about 5%. For Shaanxi Province, China, the annual output of chestnut was 40,400 tons in 2008, which increased by 13.0% from 35,800 tons in 2007 (NBSC, 2011). In China and some countries, chestnut flour is a popular food ingredient to process different foods (Benzo et al., 1999; Koyuncu et al., 2004; Sacchetti and Pinnavaia, 1999). The conventional chestnut flour processing technology demonstrates that shells and pellicles of chestnuts are peeled firstly, then the chestnut kernels are dried to reduce their moisture content to approximately below 10% w.b. (wet basis), and finally dried chestnut kernels are ground into flour (Shao and Zhang, 2009).

Hot air drying is a traditional drying method. However, it has many disadvantages, such as long time processing, high energy consumption and low heating efficiency. Koyuncu et al. (2004) studied drying characteristics and energy requirement for drying in-shell chestnuts with forced hot air, and reported that when the chestnuts were dehydrated from the initial moisture content of about 50% w.b. to 7.4% w.b., the shortest dry time of 43 h was obtained at 70 °C and 0.1 m/s velocity, and the longest drying time of 212 h was found at 40 °C and 0.5 m/s velocity. The experiment made by Attanasio et al. (2004) also showed that the drying time needed to reduce moisture content of in-shell chestnuts from original 56% w.b. to 20% w.b. was about 51 h at 40 °C or 37 h at 60 °C using 0.5 m/s hot air speed. More than 160 h was needed if the moisture content was reduced to about 10% w.b. When the chestnut kernels were cut into slice state less than 0.3 cm thickness and their moisture were dehydrated from original content, about 55% w.b. to 10% w.b., 6–8 h was needed at 50–60 °C or 2–3 h was needed at 70–80 °C drying process (Li, 2008). Although high air temperature reduced drying time, browning/blackening appeared in dried chestnuts, influencing chestnut overall quality, price and marketability. Normally, for Chinese chestnut (*Castanea mollissima*), drying temperature not higher than 60 °C can guarantee chestnut without brown color and have acceptable product quality (Jiang et al., 2004; Li, 2008).

Use of radio-frequency (RF) or microwave (MW) energy for dielectric heating of food materials is an important application area (Nelson, 1994). RF or MW heating has been studied as a possible method for drying agricultural products (Díaz et al., 2003; Jumah, 2005; Medeni, 2001; Varith et al., 2007; Villalpando-Guzman et al., 2011). This novel drying method with RF and MW energy provides shorter time, higher energy efficiency and better product quality as compared to conventional hot air heating (Díaz et al., 2003; Dong et al., 2011; Duan et al., 2011; Varith et al., 2007; Zhang et al., 2006). Knowledge on dielectric properties of agricul-

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http://dx.doi.org/10.1016/j.jfoodeng.2012.04.014

tural products or foods is critical to develop effective dielectric drying with RF or MW energy. The dielectric properties of usual interest in most applications are the dielectric constant $\varepsilon'$ and loss factor $\varepsilon''$, the real part and imaginary part, respectively, of the relative complex permittivity $\varepsilon^*$, $\varepsilon^* = \varepsilon' - j\varepsilon''(j = \sqrt{-1})$. The dielectric constant indicates the ability of a material to store electric energy in the electric field in the material, and the loss factor is associated with energy dissipation in the material or the conversion ability from electric energy to heat energy.

A lot of studies on agricultural products and foods have presented that the dielectric properties are functions of frequency, moisture content and temperature (Guo et al., 2008, 2010a; Jiao et al., 2011; Sharma and Prasad, 2002; Trabelsi and Nelson, 2006; Wang et al., 2003b). Our previous work on fresh chestnut and chestnut weevil also showed that their dielectric properties are influenced by frequency and temperature (Guo et al., 2011a) but moisture effects are not covered. During chestnut drying with RF and MW energy, the moisture content degrades gradually. The fundamental knowledge of dielectric properties of chestnut under different frequencies, moisture contents and temperatures may help us to understand the interaction between the chestnuts and electromagnetic field. The permittivity data of chestnut can be useful to establish a heat simulation model of drying by RF and MW energy. Such a simulation model can guide the design of industrial equipments and improve the drying efficiency for chestnuts with RF and MW energy. However, no information is available on chestnuts' dielectric properties over a wide frequency range at different moisture contents and temperatures. Therefore, the objectives of the study were (1) to measure the dielectric constant and loss factor of chestnut flour in five moisture contents and temperatures over a frequency range from 10 to 4500 MHz, (2) to provide the theoretical equations describing chestnut flour's dielectric properties as function of moisture content and temperature at interested frequencies, and (3) to evaluate the application prospect of drying chestnut using RF and MW energy based on penetration depth. The study will offer information for drying chestnut with RF or MW energy in whole or later drying process.

## 2. Materials and methods

### 2.1. Materials

Fresh mature chestnuts (Zhen'an variety) were harvested from Zhen'an County, Shaanxi Province, China in 2011. The original moisture content of the fresh kernels, without shells and pellicles, was 59.3 ± 0.4% w.b.

### 2.2. Sample preparation

Since the close contact between open-ended coaxial-line probe surface and materials is needed in measuring dielectric properties of materials, intact chestnut kernel without plat surface cannot be used to obtain permittivity values directly. Therefore, the chestnut kernels in dried state were ground into flour. Then flour samples in different moisture contents were prepared and compressed to obtain samples with flat surface and similar density to true kernel density at corresponding moisture content. The detailed information about sample preparation is showing below.

Thirty kilograms fresh chestnuts with shells were dried at 40 °C in a WG-71 forced-air oven (Tianjin Taisite Instrument Co., Ltd., Tianjin, China) to obtain dehydrated chestnuts, which would be ground into flour in a grinder. Every one or two days, about 200 g samples were taken out from the oven. After removing shells and pellicles, one lot was used to measure moisture content and another lot was used to determine true density of kernel at corresponding moisture content. The moisture content of chestnut kernels was determined by drying triplicate test samples of sliced nuts in 1–1.5 mm thickness at 100 °C in a ZKF030 vacuum drying oven (Shanghai Experimental Instrument Factory Co., Ltd., Shanghai, China) until constant weight (AOAC, 1998). The mean moisture content and standard deviation were used in the results. The true density of chestnuts' kernel without shells and pellicles was measured with liquid displacement method. Water was used as the immersion liquid. The true density was determined by dividing the weight of randomly selected intact samples (~25 g) by the volume occupied by those samples as measured with water in 100 ml pycnometer. The experiments were completed as soon as possible to avoid water absorption in the samples. True density experiments were replicated four times and the mean density and standard deviation were calculated from the replicated results. A regression equation was developed to describe the relationship between true density and moisture content.

When the chestnuts in the oven were dehydrated to about 10% w.b., they were taken out from the oven followed by being ground in a grinder. The initial moisture content of chestnut flour was 11.6 ± 0.1% w.b., and the chestnut flour of 80 mesh fineness was used in the experiment. Flour samples at different moisture levels were obtained by spraying deionized water on each 200 g chestnut flour. The moisture contents of the prepared flour samples were checked by the oven drying method at 130 °C for 1 h (AOAC, 1998). According to this method, the flour samples in moisture content of 20.6 ± 0.1%, 30.2 ± 0.1%, 39.3 ± 0.0% and 48.0 ± 0.0% w.b. were prepared. The highest moisture content was lower than that of fresh chestnuts (59.3% w.b.), since the water would be pressed out when making homogeneous samples if the moisture content of flour was too high.

It is known that the permittivities are density-dependent, so the corresponding true density of kernel at the moisture content of 11.6%, 20.6%, 30.2%, 39.3% and 48.0% w.b. were calculated from obtained regression equation between moisture content and true density of chestnut kernel. A known amount of chestnut flour was compressed with a cylindrical holder (22 mm in inner diameter and 100 mm in height) and a hydraulic press to make homogeneous cylindrical samples (~30 mm in height) whose density matched with true density of chestnut kernel at the same moisture content. The detailed information on preparing cylindrical samples can be referred in former publications (Guo et al., 2008, 2011a). Three compressed chestnut flour samples at each moisture content level were prepared for permittivity measurements.

### 2.3. Measurement of dielectric properties

The permittivity determinations of compressed chestnut flour samples were obtained with an Agilent Technologies 85070B open-ended coaxial-line probe, an Agilent Technologies E5071C network analyzer (Agilent Technologies, Penang, Malaysia), a temperature-controlled stainless steel cylindrical sample holder built for use with the 85070B probe and a constant temperature water bath (DK-98-1, Tianjin Taisite Instrument Co., Ltd., Tianjin, China). Permittivities, dielectric constant ($\varepsilon'$) and loss factor ($\varepsilon''$) were calculated with Agilent Technologies 85070D Dielectric Probe Kit Software, which provided values of dielectric constant and loss factor from the reflection coefficient of the material in contact with the active tip of the probe. Permittivity measurements were done at 51 frequencies on a logarithmic scale from 10 to 4500 MHz. The frequency range covers 27, 40, 915 and 2450 MHz, which are allocated by US Federal Communication Commission for ISM (Industrial, Scientific and Medical) applications. The network analyzer and probe were calibrated according to instruction on permittivity measurements (Agilent Technologies, 2005). A measurement was made on 25 °C deionized water to verify whether the obtained permittivity values matched well with known data. Otherwise, the probe was calibrated again until the measured permittivity values were acceptable.

### 2.4. Procedures

After the network analyzer was turned on 1 h, calibration on the network analyzer and 85070B probe was done. The pressed chestnut flour sample was placed in a stainless steel cylindrical sample holder (25 mm in diameter and 40 mm in height), which was welded to a stainless steel plate. The plate was submerged in a constant temperature water bath. The water bath was lifted to make the compressed chestnut samples contact well with the 58070B probe. The temperature was controlled by circulating water in water bath, and it was set at 20, 30, 40, 50 and 60 °C in sequence. At each temperature, dielectric properties of samples were measured in triplicate. In preliminary experiments, a type-T thermocouple temperature sensor was inserted into the center of the cylindrical chestnut samples to monitor the sample temperature. It showed that about 15 min was needed for the sample temperature to reach the next set level. Mean values of triplicate measurements at each temperature were reported.

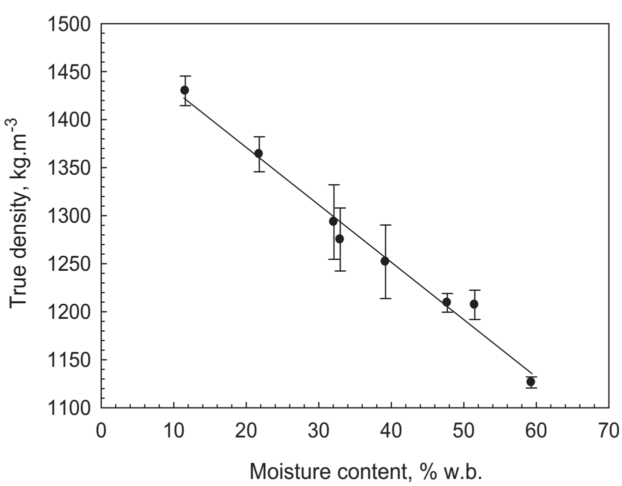


**Fig. 1.** Effect of moisture content on true density of chestnut kernel, $R^2 = 0.97$.

### 2.5. Penetration depth

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

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

where $d_p$ is penetration depth in m, $f$ is frequency of RF or MW in Hz, $c$ is the speed of light in free space ($3 \times 10^8$ m s$^{-1}$), $\varepsilon'$ and $\varepsilon''$ are the measured dielectric constant and dielectric loss factor values of a material, respectively.

## 3. Results and discussions

### 3.1. Effect of moisture content on true density of chestnut kernel

Fig. 1 shows the effect of moisture content on true density of chestnut kernel. The true density decreased linearly from 1430 to 1126 kg m$^{-3}$ as the moisture content increased from 11.6% to 59.3% w.b. The relationship, with the linear coefficient of determination ($R^2$) of 0.97, can be expressed by following linear equation:

$$\rho = -5.98\,W + 1491.1 \qquad (R^2 = 0.97) \tag{2}$$

where $\rho$ is true density of chestnut kernel in kg m$^{-3}$ and $W$ is moisture content in % w.b, $11.6 \leqslant W \leqslant 59.3$.

Eq. (2) illustrates that the increase rate in chestnut kernel volume was larger than in weight due to the increased moisture. The result was similar to those reported for popcorn over the moisture content range of 8.95–17.12% w.b. (Ersan, 2006), for soybean from 8.7% to 25.0% w.b. (Deshpande et al., 1993), for cowpea seed from 12.01% to 38.90% d.b. (dry basis) (Ibrahim, 2007), and for pigeonpea from 10% to 30% w.b. (Singh and Kotwaliwale, 2010).

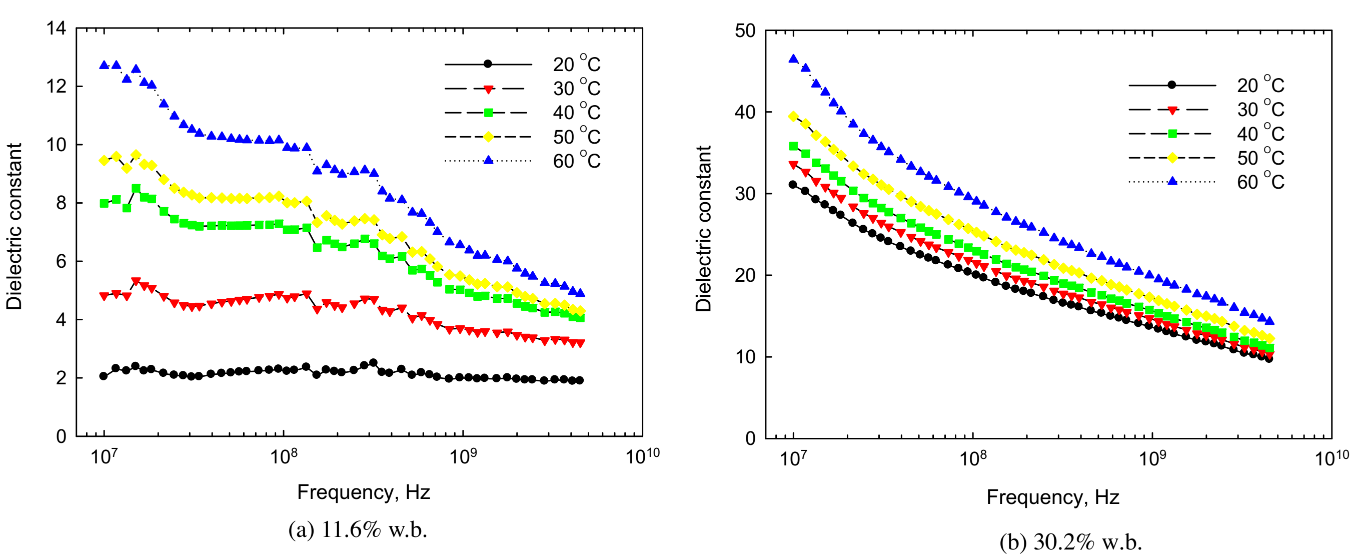


**Fig. 2.** The obtained mean values of dielectric constants of compressed chestnut flour samples with moisture content of 11.6% w.b. (a) and 30.2% w.b. (b) at indicated temperatures over the frequency range from 10 to 4500 MHz.

## 3.2. Dielectric constant

### 3.2.1. Frequency-dependent dielectric constant

The obtained mean values of dielectric constants of compressed chestnut flour samples in moisture content of 11.6% w.b. (Fig. 2a) and 30.2% w.b. (Fig. 2b) are shown in Fig. 2 at indicated temperatures over the frequency range from 10 to 4500 MHz. Fig. 2a shows that the dielectric constant of compressed chestnut flour samples at 11.6% w.b. almost kept constant all over the frequency range at 20 °C, and decreased with increasing frequency at other temperatures. The dielectric constant decreased more greatly with increasing frequency at higher temperatures. For example, when the frequency increased from 10 to 4500 MHz, the dielectric constant decreased from 4.82 to 3.21 at 30 °C, and from 12.69 to 4.88 at 60 °C. For the samples in moisture content of 30.2% w.b., the dielectric constant decreased with increasing frequency at any given temperature, and decreased sharply at higher temperatures (Fig. 2b). Fig. 2 also illustrates that the dielectric constant increased with an increase in temperature from 20 to 60 °C at a given frequency. The dielectric constants of other compressed chestnut flour samples in moisture contents of 20.6%, 39.3% and 48.0% w.b. also decreased with increasing frequency. At 30 °C, they decreased from 13.3 to 5.3 in 20.6% w.b., from 46.4 to 14.4 in 39.3% w.b. and from 60.5 to 20.7 in 48.0% w.b. when the frequency increased from 10 to 4500 MHz.

### 3.2.2. Moisture content- and temperature-dependent dielectric constant

The obtained dielectric constants of compressed chestnut flour samples as function of moisture content and temperature at 27 MHz (Fig. 3a), 40 MHz (Fig. 3b), 915 MHz (Fig. 3c) and 2450 MHz (Fig. 3d) are shown in Fig. 3. It was observed that at a given frequency, the dielectric constants increased with increasing moisture content and temperature. For example, at 27 MHz, when temperature increased from 20 to 60 °C, the dielectric constant increased from 2.1 to 10.7 at 11.6% moisture content w.b., from 25.0 to 36.5 at 30.2% w.b. and from 41.5 to 53.9 at 48.0% w.b.(Fig. 3a). At 915 MHz, when the moisture content increased from 11.6% to 48.0% w.b., the dielectric constant increased from 2.0 to 25.5 at 20 °C, from 5.0 to 28.7 at 40 °C and from 6.6 to 33.3 at 60 °C

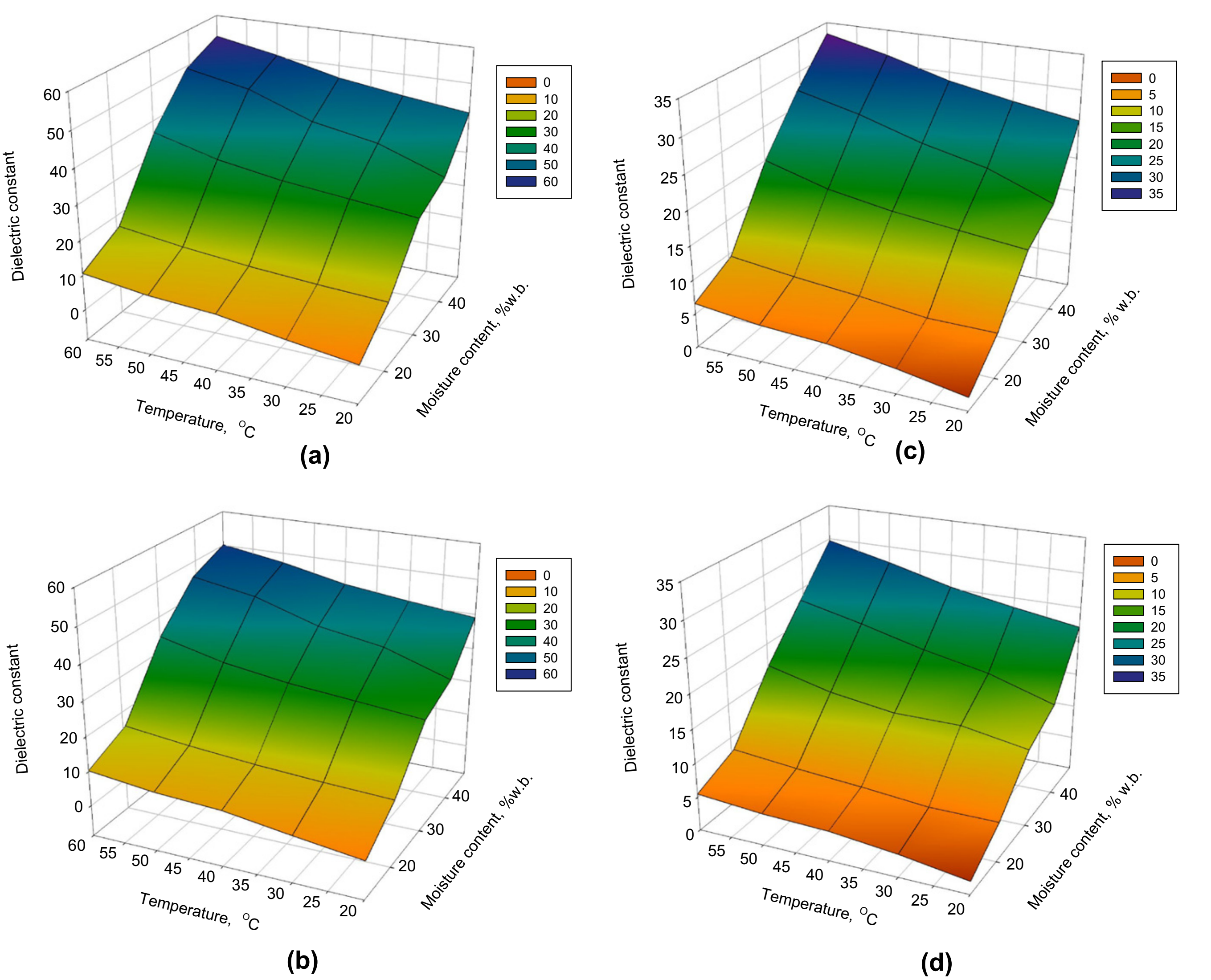


**Fig. 3.** The obtained dielectric constants of compressed chestnut flour samples as function of moisture content and temperature at 27 MHz (a), 40 MHz (b), 915 MHz (c) and 2450 MHz (d) over a moisture content range from 11.6% to 48.0% w.b. and a temperature range from 20 to 60 °C.

(Fig. 3c). The increased dielectric constant with increasing moisture content and temperature at a given frequency was also been reported in some legume flours (Guo et al., 2008, 2010a; Jiao et al., 2011) and wheat flour (Nelson and Trabelsi, 2006) in the frequency range of 10–1800 MHz.

The data in Fig. 3 were analyzed using Design-Expert 7.1.6 to obtain regression models describing the dielectric constants of chestnut flour samples as function of moisture content and temperature. The regressed polynomial models at 27, 40, 915 and 2450 MHz are given in Eqs. (3)–(6), respectively, where $W$ is moisture content in % w.b., $11.6 \leqq W \leqq 48.0$, and $T$ is temperature in °C, $20 \leqq T \leqq 60$. Only Eq. (6) was a second-degree polynomial, others were third-degree polynomials.

$$\varepsilon'_{27\text{MHz}} = 16.75 - 2.40W - 0.202T + 0.0124WT + 0.127W^2 + 2.71 * 10^{-3}T^2 - 1.97 * 10^{-4}W^2T + 7.89 * 10^{-5}WT^2 - 1.40 * 10^{-3}W^3 - 2.05 * 10^{-5}T^3 \quad (3)$$

$$\varepsilon'_{40\text{MHz}} = 14.95 - 2.21W - 0.135T + 0.0124WT + 0.116W^2 + 1.25 * 10^{-3}T^2 - 1.89 * 10^{-4}W^2T + 6.32 * 10^{-5}WT^2 - 1.27 * 10^{-3}W^3 - 9.22 * 10^{-6}T^3 \quad (4)$$

$$\varepsilon'_{915\text{MHz}} = 6.103 - 0.83W - 6.822 * 10^{-4}T + 3.531 * 10^{-3}WT + 0.047W^2 - 3.42 * 10^{-4}T^2 - 5.036 * 10^{-5}W^2T + 4.896 * 10^{-5}WT^2 - 4.610 * 10^{-4}W^3 + 7.10972 * 10^{-7}T^3 \quad (5)$$

$$\varepsilon'_{2450\text{MHz}} = 2.58 - 0.0105W - 0.089T + 4.33 * 10^{-3}WT + 6.11 * 10^{-3}W^2 + 9.92 * 10^{-4}T^2 \quad (6)$$

Analysis of variance (ANOVA) was carried out to determine whether moisture content and temperature had significant influence on these models. Table 1 shows ANOVA results for Eqs. (3)–(6). The linear terms and interaction term of $W$ and $T$ had very strong influence on these models at 0.005 significance level (significance of probability $p < 0.005$). The quadratic term of $W$ also had obvious influence on the models at 915 MHz (Eq. (5)) and 2450 MHz (Eq. (6)) at 0.005 significance level. The term of $W^3$ was a significant factor in regressed third-degree polynomial expressions.

Each model provided a good fit to the experimental data at the significance level of 0.0001 and with a value for coefficient of determination of greater than 0.994. Accordingly, it can be stated that Eqs. (3)–(6) are acceptable enough for predicting the dielectric constants of chestnut at any given moisture content and temperature over the observed range of each variable at 27, 40, 915 and 2450 MHz, respectively.

### 3.3. Dielectric loss factor

#### 3.3.1. Frequency-dependent dielectric loss factor of chestnut

Fig. 4 shows the obtained mean values of dielectric loss factors of compressed chestnut flour samples with moisture contents of 11.6% w.b. (a) and 30.2% w.b. (b and c) in the frequency range of 10–4500 MHz at temperature from 20 to 60 °C. At a given temperature, the loss factor decreased with an increase in frequency of the electric field. The decrease with increasing frequency was more

**Table 1**
Significance of probability ($p$) of regressed models of Eqs. (3)–(6) for compressed chestnut flour samples at four frequencies of interest.

| Variances and $R^2$ | 27 MHz Eq. (3) | 40 MHz Eq. (4) | 915 MHz Eq. (5) | 2450 MHz Eq. (6) |
|---|---|---|---|---|
| $W$ | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| $T$ | 0.0007 | 0.0012 | 0.0005 | <0.0001 |
| $WT$ | 0.0004 | 0.0010 | <0.0001 | <0.0001 |
| $W^2$ | 0.5306 | 0.9563 | 0.0005 | <0.0001 |
| $T^2$ | 0.1795 | 0.2520 | 0.2341 | 0.0495 |
| $W^2T$ | 0.2201 | 0.2320 | 0.6374 | –[a] |
| $WT^2$ | 0.5723 | 0.6463 | 0.6012 | – |
| $W^3$ | <0.0001 | <0.0001 | 0.6017 | – |
| $T^3$ | 0.9076 | 0.9579 | 0.9935 | – |
| Model | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| $R^2$ | 0.9952 | 0.9945 | 0.9961 | 0.9976 |

[a] Dashes in the table indicate the term was not included in regressed model.

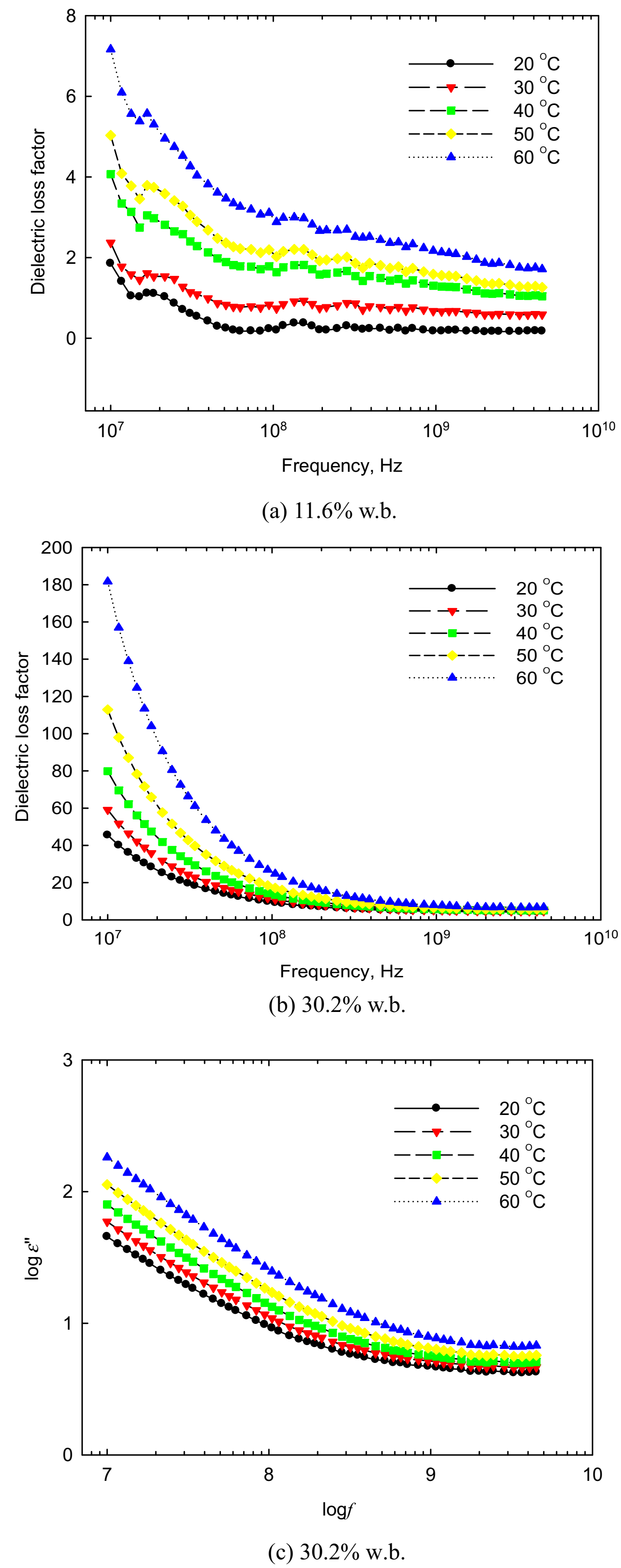


**Fig. 4.** The obtained mean values of dielectric loss factors of compressed chestnut flour samples in moisture content of 11.6% w.b. (a) and 30.2% w.b. (b and c) at indicated temperatures over the frequency range from 10 to 4500 MHz.

rapid at lower frequencies (i.e. 100 MHz) than at higher frequencies. For example, when the frequency increased from 10 to 100 MHz, the loss factors of compressed chestnut flour samples with the moisture content of 11.6% w.b. and 30.2% w.b. decreased from 1.85 and 45.5 to 0.20 and 9.2, then decreased from 0.20 and 9.2 to 0.17 and 4.3 when the frequency increased from 100 to 4500 MHz, respectively. Moreover, the loss factor at higher temperatures decreased more than at lower temperatures over the whole frequency range. For example, the loss factors were 45.5 and 181.7 at 20 and 60 °C for the samples with moisture content of 30.2% w.b. at 10 MHz, respectively, but they decreased to 4.3 and 6.8 at 2450 MHz, and decreased by 41.2 and 174.9, respectively.

In order to observe the frequency dependence of loss factor clearly, the vertical axis in linear scale in Fig. 4(b) was presented in logarithmic scale in Fig. 4(c). Fig. 4(c) illustrates that log $\varepsilon''$ and log $f$ had obvious negative linear relationship below about 100 MHz. Several studies had demonstrated that the ionic conduction plays dominant role in loss mechanism at RF range below 300 MHz, which causes the log of loss factor decreasing linearly with an increase of log of frequency (Guo et al., 2010b, 2011b; Wang et al., 2005; Zhu et al., 2012). At any given frequency, the loss factor increased with increasing temperature, and the increase was greater at lower frequencies than at higher ones. The decreased dielectric loss factors as increasing frequency from 10 to 4500 MHz were also noticed on compressed chestnut samples in moisture contents of 20.6%, 39.3% and 48.0% w.b., and the decrease was 59%, 95% and 97% at 20 °C, respectively. Higher moisture content, more decrease.

### 3.3.2. Moisture content- and temperature-dependent dielectric loss factor

The measured mean values of dielectric loss factors of compressed chestnut flour samples as function of moisture content and temperature at 27 MHz (Fig. 5a), 40 MHz (Fig. 5b), 915 MHz (Fig. 5c) and 2450 MHz (Fig. 5d) are shown in Fig. 5. It expresses that the dielectric loss factor increased as either moisture content or temperature increased.

When the dielectric materials were placed in an alternating electric field, they convert electric energy at RF and MW frequencies into heat (Wang et al., 2003a). The power dissipated per unit volume in a nonmagnetic, uniform material exposed to RF or

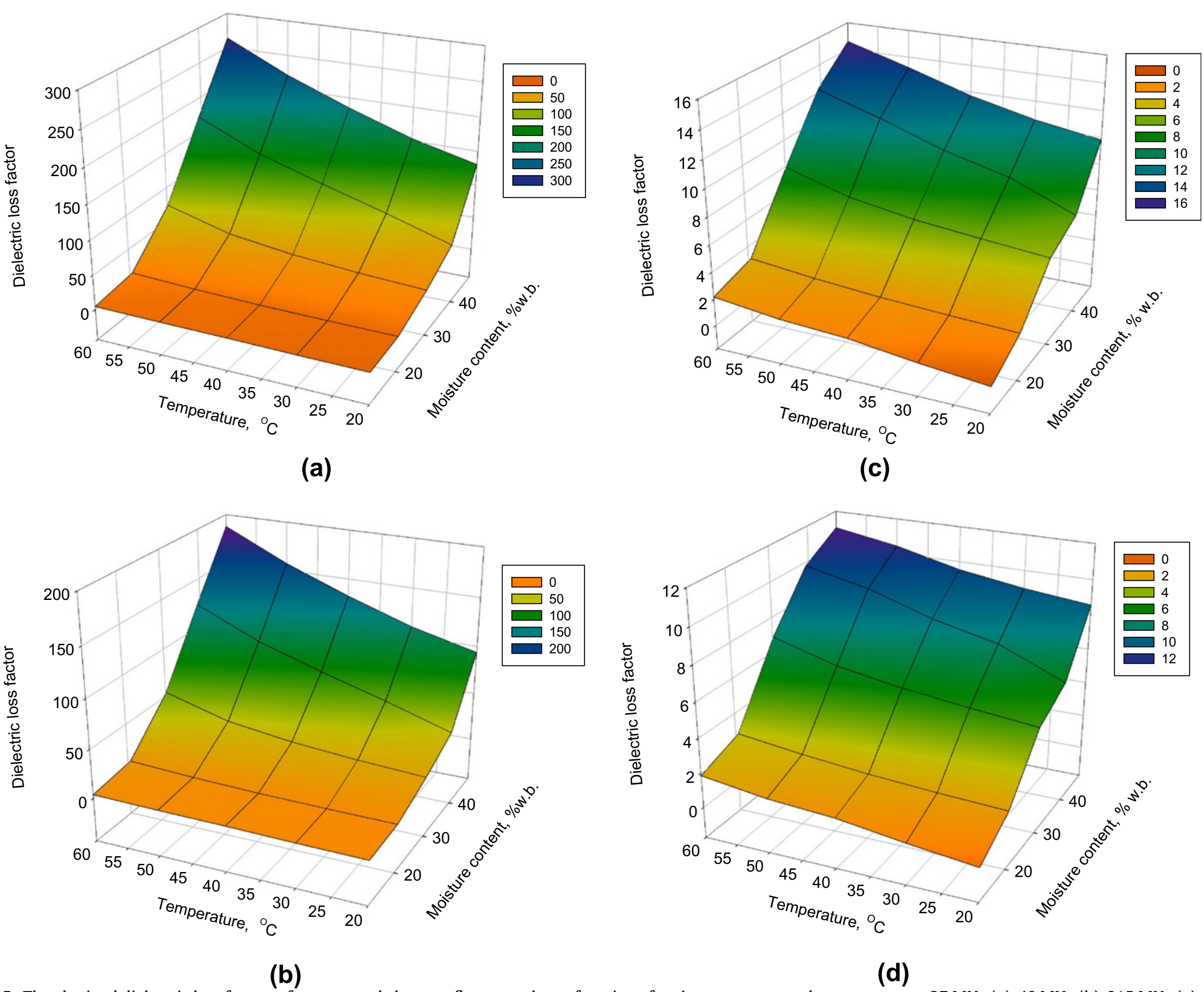


**Fig. 5.** The obtained dielectric loss factors of compressed chestnut flour samples as function of moisture content and temperature at 27 MHz (a), 40 MHz (b), 915 MHz (c) and 2450 MHz (d) over a moisture content range from 11.6% to 48.0% w.b. and a temperature range from 20 to 60 °C.

MW fields is proportional to the dielectric loss factor of the material (Nelson, 1996). That is, the higher the dielectric loss factor, the more the power is absorbed by the material, and the higher the rate of temperature increases. Fig. 5 shows that the chestnut had larger dielectric loss factor values at higher temperatures than at lower temperatures. It means the chestnut at higher temperatures will absorb more energy than at lower ones, which will result in non-uniform heating. On the other hand, the chestnut in higher moisture content had larger loss factor values than in lower moisture content. During RF or MW drying, the portion with low moisture content will absorb less energy, which will be beneficial to heating uniformity when chestnuts in different moisture contents are heated with RF or MW energy in electric field.

The second- or third-degree polynomial relationships for the best fit to correlate the dielectric loss factor and moisture content and temperature in Fig. 5a–d were obtained as below, respectively:

$$\varepsilon''_{27\mathrm{MHz}} = 123.69 - 9.27W - 2.95T + 0.103WT + 0.173W^2 + 0.0180T^2 \quad (7)$$

$$\varepsilon''_{40\mathrm{MHz}} = 84.64 - 6.33W - 2.07T + 0.0728WT + 0.120W^2 + 0.0128T^2 \quad (8)$$

$$\varepsilon''_{915\mathrm{MHz}} = -1.36 + 0.139W - 0.069T + 2.46 * 10^{-3}WT + 1.17 * 10^{-3}W^2 + 1.13 * 10^{-3}T^2 \quad (9)$$

$$\varepsilon''_{2450\mathrm{MHz}} = 5.32 - 0.680W - 0.098T + 4.54 * 10^{-3}WT + 0.030 * 10^{-3}W^2 + 1.41 * 10^{-3}T^2 - 5.74 * 10^{-5}W^2T + 3.30 * 10^{-7}WT^2 - 2.94 * 10^{-4}W^3 - 7.30 * 10^{-6}T^3 \quad (10)$$

where $W$ is in % w.b.,$11.6 \leqq W \leqq 48.0$, and $20\,^\circ\mathrm{C} \leqq T \leqq 60\,^\circ\mathrm{C}$. Only the regression model at 2450 MHz, that is Eq. (10), is third-degree polynomial. Others are second-degree polynomials.

Table 2 shows ANOVA results for Eqs. (7)–(10). The linear terms and interaction term of $W$ and $T$ had very strong influence on these models at a 0.005 significance level ($p < 0.005$). The quadratic term of $W$ had strong influence on Eqs. (7), (8), and (10). The term of $W^3$ had very significant influence on the model at a significance level of 0.0001. The significant probability of each model was less than 0.0001 and $R^2$ was above 0.993. It suggests that these models can be used to precisely estimate the dielectric loss factor value of chestnut from known moisture content and temperature at selected frequencies.

### 3.4. Penetration depth

The penetration depths calculated from obtained mean values of dielectric constants and loss factors of compressed chestnut flour samples are listed in Table 3 at four interested frequencies, five temperatures and five moisture content levels. The penetration depth decreased with increasing frequency, moisture content and temperature. For example, for chestnut flour samples in moisture content of 11.6% w.b. and at 60 °C, the penetration depth decreased from 1270.9 mm at 27 MHz to 24.9 mm at 2450 MHz.

**Table 2**
Significance of probability ($p$) of regressed models of Eqs. (7)–(10) for compressed chestnut flour samples at four frequencies of interest.

| Variances and $R^2$ | 27 MHz Eq. (7) | 40 MHz Eq. (8) | 915 MHz Eq. (9) | 2450 MHz Eq. (10) |
|---|---|---|---|---|
| $W$ | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| $T$ | <0.0001 | <0.0001 | <0.0001 | 0.0001 |
| $WT$ | <0.0001 | <0.0001 | <0.0001 | 0.0009 |
| $W^2$ | <0.0001 | <0.0001 | 0.0525 | 0.0002 |
| $T^2$ | 0.0410 | 0.0403 | 0.0297 | 0.1200 |
| $W^2T$ | –[a] | – | – | 0.0531 |
| $WT^2$ | – | – | – | 0.9595 |
| $W^3$ | – | – | – | <0.0001 |
| $T^3$ | – | – | – | 0.5245 |
| Model | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| $R^2$ | 0.9940 | 0.9940 | 0.9932 | 0.9965 |

[a] Dashes in the table indicate the term was not included in regressed model.

**Table 3**
The calculated penetration depths in mm from obtained mean values of dielectric constants and loss factors of compressed chestnut flour samples at four interested frequencies over five temperatures and five moisture content levels.

| Moisture content (% w.b.) | Frequency (MHz) | Temperature (°C) | | | | |
|---|---|---|---|---|---|---|
| | | 20 | 30 | 40 | 50 | 60 |
| 11.6 | 27 | 3553.8 | 2886.1 | 1831.9 | 1549.3 | 1270.9 |
| | 40 | 3266.8 | 2608.0 | 1535.2 | 1301.4 | 1029.0 |
| | 915 | 396.6 | 142.3 | 86.2 | 74.1 | 59.4 |
| | 2450 | 163.4 | 60.1 | 37.1 | 31.5 | 24.9 |
| 20.6 | 27 | 1978.3 | 1679.5 | 1317.6 | 898.8 | 626.5 |
| | 40 | 1542.8 | 1315.5 | 1050.5 | 740.4 | 525.4 |
| | 915 | 80.0 | 73.4 | 66.8 | 59.3 | 52.1 |
| | 2450 | 32.1 | 29.3 | 26.5 | 23.4 | 20.7 |
| 30.2 | 27 | 439.3 | 372.2 | 305.5 | 244.9 | 182.2 |
| | 40 | 371.8 | 317.4 | 262.6 | 211.2 | 157.2 |
| | 915 | 39.6 | 37.3 | 35.1 | 32.4 | 28.6 |
| | 2450 | 15.4 | 14.6 | 13.9 | 13.1 | 11.9 |
| 39.3 | 27 | 243.7 | 177.3 | 145.3 | 126.2 | 107.0 |
| | 40 | 212.6 | 154.3 | 125.9 | 108.7 | 91.7 |
| | 915 | 35.0 | 28.9 | 26.3 | 23.7 | 21.7 |
| | 2450 | 13.9 | 11.8 | 11.1 | 10.2 | 9.8 |
| 48.0 | 27 | 124.8 | 113.2 | 101.4 | 97.9 | 83.0 |
| | 40 | 108.0 | 97.6 | 87.1 | 78.8 | 71.0 |
| | 915 | 26.0 | 24.8 | 23.2 | 21.5 | 20.1 |
| | 2450 | 10.9 | 10.8 | 10.5 | 10 | 9.8 |

When temperature increased from 20 to 60 °C, the depth decreased from 1978.3 to 626.5 mm for samples in 20.6% w.b. at 27 MHz. At 27 MHz and 60 °C, the depth decreased from 1270.9 to 83.0 mm as the moisture content increased from 11.6% to 48.0% w.b. Similar frequency, moisture content and temperature dependence of penetration depth was also noticed in some legume flours (Guo et al., 2010a; Jiao et al., 2011).

It is evident that the penetration depth for RF below 100 MHz is superior to the ones for MW (Table 3), which means the uniformity under dielectric heating at lower electric wave frequencies is better than at microwave frequencies. RF below 100 MHz can provide practical treatment with large depth, while MW can be used in small depth treatment for drying chestnut with dielectric heating.

## 4. Conclusions

The dielectric constants and dielectric loss factors of compressed chestnut flour samples were dependent on moisture content and temperature of samples, and frequency of the applied electric field. They increased with increasing moisture content and temperature and decreasing frequency. The changes in the values of dielectric constant and loss factor were greater at lower frequencies than at higher ones. The second- or third-degree polynomial models could be used to describe permittivity values as function of moisture content and temperature at interested frequencies used in ISM. Moisture content and temperature had strong effect on permittivities. The penetration depth decreased with increasing frequency, moisture content and temperature. RF range below 100 MHz and MW can be used in large-scale treatment and small-scale treatment, respectively. They can be applied in whole process or the later part in chestnut drying. The study offers new information on the dielectric properties of chestnuts, which can be useful to establish a heat simulation model of chestnut drying by RF and MW energy. Such a simulation model can help for the design of industrial equipments and the choice of drying technique for chestnut efficiently.

## Acknowledgments

This research work was sponsored by Grant from National Natural Science Foundation of China (31171720), Chinese Universities

Scientific Fund (QN2009043, Northwest A&F University) and seed grant from Yangling International Academy of Modern Agriculture.

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