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Research Paper

Temperature-dependent dielectric properties of chestnut and chestnut weevil from 10 to 4500 MHz

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The dielectric properties of chestnut and chestnut weevil at five temperatures between 20 °C and 60 °C over the frequency range from 10 to 4500 MHz were measured with an open-ended coaxial-line probe and network analyser. The dielectric constants (ε') of both materials decreased with increasing frequency. The dielectric loss factor (ε'') of chestnut decreased with increasing frequency below about 3000 MHz, and slightly increased above 3000 MHz. The ε'' of chestnut weevil decreased with increasing frequency to a minimum value at about 1000 MHz. Below the turn point, the value of ε'' increased with increasing temperature, and decreased with temperature above that point. The ε' and ε'' of chestnut and ε' of chestnut weevil increased with increasing temperature. The penetration depth decreased with the increase of either frequency or temperature. Dielectric heating below 100 MHz might provide practical applications in controlling chestnut weevil due to potential differential heating and sufficient penetration depth. The study offers useful information on dielectric properties of chestnut and chestnut weevil in developing thermal treatments for postharvest disinfestation based on electromagnetic energy.

1. Introduction

Chestnut (*Castanea mollissima*) is one of the most popular nuts in the world with a unique flavour and taste. China is the largest chestnut producing country, followed by Japan, Korea, Spain, Portugal, France and Italy (Biju Cletus & Carson, 2008). The chestnut has relatively high moisture content and is rich in carbohydrate and low in fat, and thus it is susceptible to insect damage in the field or following harvest (Tanaka, Kotobuki, & Kakiuchi, 1981). Annually, about 20–30% of harvested chestnuts in China are wasted and spoiled by insect infestation and mildew (Zhang, Dang, & Zhang, 2001). Chestnut weevil (*Curculio elephas*) is recognised as a major pest in harvested chestnuts.

Insect infestations degrade the flavour and appearance of chestnut, reduce its market price as a foodstuff, and cause technical barriers for export. Traditionally, chemical fumigation (using SO_2, phosphine, or methyl bromide) is used to control insects in postharvest agricultural products. However, SO_2 and phosphine treatments are not only harmful to workers and consumers, but they can also increase resistance in the pest population (Gao, Tang, Wang, Powers, & Wang, 2010). Also, under the Montreal Protocol (UNEP, 1992), methyl bromide was defined as a chemical that

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contributes to the depletion of the ozone layer. Some developed countries have ceased using and producing methyl bromide since 2005. Developing countries will stop its productions and applications in 2015. There is therefore an increasing interest in developing non-chemical alternative treatments.

Conventional thermal treatment, which relies on circulating heated air, water or steam, is widely used as non-chemical methods to control insect pests in agric-products. Most insects in postharvested fruits and nuts can be controlled by thermal treatments over a temperature range of 46–56 °C (Johnson, Wang, & Tang, 2003, 2004; Wang, Ikediala, Tang, & Hansen, 2002a, 2002b). However, the disadvantages of conventional thermal disinfestation method include a slow heating rate, a long processing time and non-uniform temperature distribution. It also impairs the flavour and appearance of the product and reduces its palatability and acceptability to consumers (Xu, 2005). Chestnut is a particularly heat-sensitive product, since higher drying temperatures (40–70 °C) reduce the sugar content and lower the starch content (Attanasio, Cinquanta, Albanese, & Matteo, 2004; Correia, Leitão, & Beirão-da-Costa, 2009). Chestnut colour becomes darker as drying temperature increases (Correia et al., 2009). Normally, to maintain the product quality, the drying temperature used in China does not exceed 60 °C (Jiang, Zhong, & Chen, 2004).

Many researchers have demonstrated that dielectric heating with radio-frequency or microwave energy can overcome the shortcomings of conventional thermal treatments for postharvest disinfestation (Ikediala, Tang, Drake, & Neven, 2000; Lagunas-Solar et al., 2007; Nelson, 1996; Wang et al., 2001, 2007a, 2007b). It is essential to obtain the dielectric properties data of both insects and products to develop radio-frequency or microwave treatment protocols. The dielectric properties of the insects and the host materials, mainly the dielectric constant ε' and the dielectric loss factor ε'', are important in improving heating uniformity, designing treatment bed depth, and evaluating the potential of differential heating between insects in host products (Nelson, Bartley, & Lawrence, 1998). Several studies have reported that dielectric loss factors of insects were higher than those of their host materials, especially below 300 MHz (Ikediala et al., 2000; Nelson & Charity, 1972; Nelson & Stetson, 1974; Wang, Tang, Cavalieri, & Davis, 2003a, 2003b). Under these conditions insects would absorb more energy at lower frequencies to reach higher lethal temperatures while their host would be heated to lower temperatures not causing quality loss (Gao et al., 2010). However, permittivity information for chestnut and chestnut weevil is still not available in the literature.

The general purpose of this research was to present the dielectric properties data for developing non-chemical insect control treatments associated with electromagnetic energy. The specific objectives of this study were to determine the permittivity data for chestnut and chestnut weevil over the frequency range from 10 to 4500 MHz at temperatures between 20 and 60 °C with an open-ended coaxial-line probe and network analyser, and to explore the possible differential heating between the chestnut weevils and the host chestnuts.

2. Materials and methods

2.1. Materials

Fresh mature chestnuts (variety Zhen'an) were harvested from Zhen'an County, located in southern Shaanxi, China in 2010. The moisture content of the kernel was 58.1% w.b. Being commonly found in the harvested chestnuts, the adult chestnut weevils with moisture content of 62.2% w.b. were collected from a local cold storage facility of chestnuts. About 100 g of chestnut weevils were used for determining permittivity.

2.2. Moisture content determination

The moisture content of fresh chestnut kernel was determined by drying triplicate test samples of sliced nuts at 100 °C until constant weight in a ZKF030 vacuum drying oven (Shanghai Experimental Instrument Factory Co. Ltd., Shanghai, China) (AOAC, 1998). The moisture content of ground chestnut flour was measured by drying triplicate about 2-g samples of well-mixed chestnut flour at 130 °C in a WG-71 forced-air oven (Tianjin Taisite Instrument Co., Ltd, Tianjin, China) for 1 h (AOAC, 1998). To compare the dielectric properties of the insects and the host chestnuts, the moisture content of the insects was also determined by drying triplicate samples of about 2–3 g for 16 h in the forced-air oven at 105 °C (Nelson et al., 1998).

The samples were cooled in a desiccator with $CaSO_4$ before reweighing to determine the moisture loss. Moisture contents were calculated from the initial and final weights of the samples.

2.3. Measurement of kernel density

The liquid displacement method was used to measure kernel density of fresh chestnut without shells. Water was used as the immersion liquid. Kernel density was determined by dividing the weight of randomly selected intact kernel samples (about 25 g) by the volume occupied by those kernels as measured with water in 100 ml pycnometers. The experiments were completed in 60 s to avoid water absorption in the kernel. Mean kernel density values were calculated from four replications. The kernel density of fresh chestnut with 58.1% moisture content (w.b.) was 1.126 g cm^{-3}.

2.4. Measurement of dielectric properties

A vector network analyser (E5071C) with an upper frequency limit of 4500 MHz, an open-ended coaxial-line probe (85070B) and a dielectric probe kit software (85070D), all from Agilent Technologies, Penang, Malaysia, were used to measure dielectric properties. Dielectric property measurements were made at 51 frequencies on a logarithmic scale from 10 to 4500 MHz. The frequency range covers 27 MHz, 40 MHz, 915 MHz and 2450 MHz, which are allocated by U.S. Federal Communication Commission for ISM (industrial, scientific and medical) applications. The port of the network analyser used in the experiment was calibrated with an open, a short, and a matched 50 Ω load in sequence. The network analyser and the open-ended probe were then connected with Agilent Technologies 53950 cable (Agilent Technologies, Penang, Malaysia). The probe was calibrated with air (open), short circuit and deionised water at 25 °C. Measurement details can be found elsewhere (Guo, Zhu, Liu, Yue, & Wang, 2010b).

2.5. *Sample preparation*

Because chestnut kernel has an irregular shape, the dielectric properties of intact chestnuts cannot be determined by open-ended coaxial-line probe technology, which is suitable for measuring liquids and needs close contact between the probe and the sample. Preliminary permittivity measurements on fresh chestnuts with flat surfaces, cut for close contact between probe and chestnut, showed poor repeatability. Therefore, homogenous chestnut samples were prepared using the methods used in previous studies (Guo, Tiwari, Tang, & Wang, 2008b, 2010a). Ten kilograms fresh of chestnuts with shell were dried at 40 °C in WG-71 forced-air oven (Tianjin Taisite Instrument Co., Ltd, Tianjin, China). The moisture content and kernel density of the samples dried in the oven were observed every day until the chestnut was dried and could be ground using a grinder. The moisture content of the ground chestnut flour was 12.6% w.b. Deionised water was sprayed onto 200 g chestnut flour in several applications to prepare chestnut flour with moisture content no more than about 30% w.b.. The sample was stirred with a glass rod to ensure that moisture was distributed uniformly. The sample was then kept over distilled water in covered desiccator to gradually absorb moisture at room temperature. It was stirred several times a day to ensure uniform water absorption, and the moisture content was checked by oven drying at 130 °C for 1 h (AOAC, 1998). After achieving the desired moisture content, the flour was sealed in plastic bags and equilibrated for three days at room temperature. The bag was shaken several times a day. The sample with 45.3% moisture content, wet basis was obtained. The final moisture content was lower than that of fresh chestnut (58.1% w.b.), since if the moisture content of flour was too high, water would be pressed out when making homogeneous samples.

In order to match the true density (1216 kg m^{-3}) of the chestnut kernel at 45.3% moisture content, a known amount of chestnut flour was compressed with a cylindrical holder (100 mm in height and 22 mm in inner diameter) and a hydraulic press to make homogeneous cylindrical samples (about 30 mm in height). Three compressed chestnut flour samples were prepared for dielectric properties measurements.

As described by Nelson, Bartley, and Lawrence (1997) and Wang et al. (2003b), for measuring the permittivities of insects with open-ended coaxial-line probes, a mortar and pestle were used to grind the adult chestnut weevil into a semidry paste. They were then transferred into two 10 ml beakers for permittivity determination.

2.6. *Procedures*

The network analyser was turned on for at least 1 h before calibration. After calibration, a compressed sample was placed in a stainless steel cylindrical cell (25 mm in diameter and 40 mm in height), which was welded to a stainless steel plate. The plate was then submerged in a constant temperature water bath (DK-98-1, Tianjin Taisite Instrument Co., Ltd., Tianjin, China). About 0.2 g the chestnut flour was added on the top of the compressed sample to ensure close contact with the coaxial-line probe. The water bath, on a laboratory jack, was raised to make good contact with the sample. The sample temperature was controlled by circulating water in the water bath. Dielectric properties of each sample were measured at 20, 30, 40, 50 and 60 °C in sequence. After triplicate measurements at each temperature, the temperature of the water bath was adjusted to the next level. Preliminary experiments showed that about 15 min was needed for the sample temperature to reach the next set level. Between replicates, the probe was cleaned with water and wiped dry. Mean values and standard deviations of triplicate measurements at each temperature were reported.

The dielectric properties of the chestnut weevil slurry were measured in two 10 ml beakers at 20, 30, 40, 50 and 60 °C. The detailed measurement procedures for samples in beakers

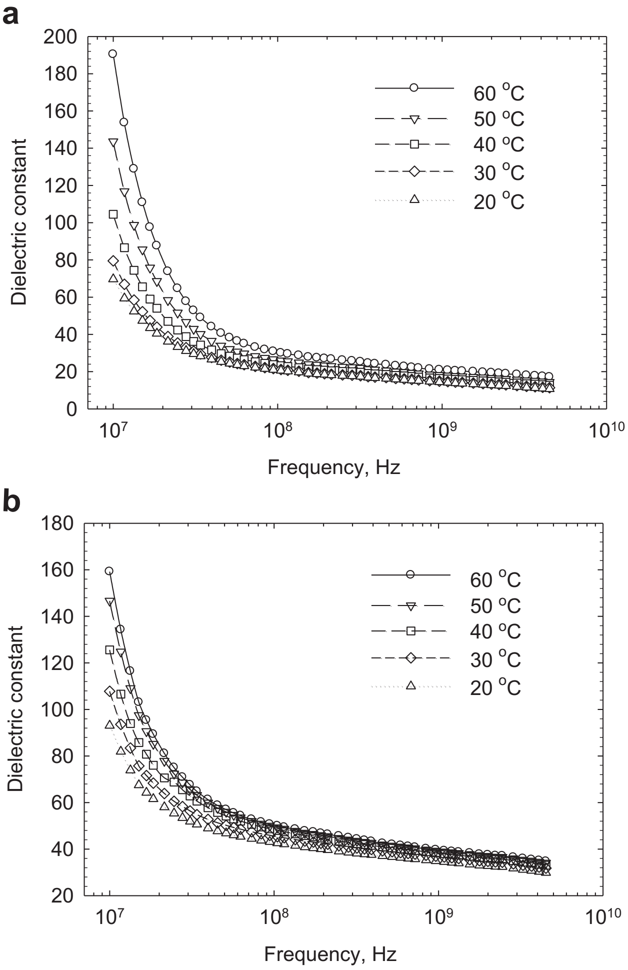

Fig. 1 – Dielectric constants of compressed chestnut flour (45.3% w.b.) (a) and chestnut weevil slurry (62.2% w.b.) (b) at indicated temperatures and 51 frequencies from 10 to 4500 MHz.

were described earlier (Guo, Liu, Zhu, & Wang, 2011a). The dielectric properties determinations were performed in duplicate. Data were expressed as means and standard deviations.

2.7. Electromagetic heating

Dielectric materials, such as most agricultural products, in electromagnetic fields of sufficient intensity may convert electromagnetic energy into heat (Wang et al., 2003b). The power P dissipated per unit volume in a nonmagnetic, uniform material exposed to RF or microwave electric fields can be expressed as (Nelson, 1996):

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

Where P is in W m^{-3}, f is the frequency in Hz, E is the electric field intensity in V m^{-1} and ε' is the dielectric loss factor of the material to be heated in the electromagnetic field. The power dissipated in a period of time provides energy to increase the temperature of the material. By neglecting the heat loss from the product sample to the ambient air and the electric field intensity difference between the insects and the host materials (Ben-Lalli, Meot, Collignan, & Bohuon, 2011; Wang et al., 2003a), the temperature difference between the insects and the host products was proportional to their ratio of dielectric loss factors. Although this was also dependent on their thermal properties, the ratio of dielectric loss factors was a good indicator for the final differential heating of insects in the host materials.

2.8. Effect of dielectric properties on penetration depth

Penetration depth, d_p, is defined as the distance in a material where the radio-frequency or microwave power of a plane wave propagating perpendicular to the surface has decreased to $1/e$ ($e = 2.718$) of the surface value (Piyasena, Dussault, Koutchma, Ramaswamy, & Awuah, 2003). It is an important parameter in evaluating heating uniformity, and designing a treatment bed depth. The penetration depth in metres of radio-frequency or microwave power in a material can be calculated according to von Hippel (1954):

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

where c is the speed of light in free space (3×10^8 m s^{-1}). After obtaining the dielectric constant and loss factor of samples, the penetration depth of compressed chestnut flour was calculated at frequencies of interest and five temperatures.

3. Results and discussion

3.1. Dielectric constants

The dielectric constants of compressed chestnut flour with moisture content of 45.3% w.b. and chestnut weevil slurry at five temperatures between 20 and 60 °C over the frequency range from 10 to 4500 MHz are shown in Fig. 1. The dielectric

Table 1 – Dielectric properties (mean ± standard deviation) of compressed chestnut flour and chestnut weevil slurry at five temperatures and six selected frequencies.

Sample	Frequency (MHz)		Temperature (°C)				
			20	30	40	50	60
Compressed chestnut flour (45.3% w.b.)	10	ε'	69.7 ± 1.4	79.5 ± 1.6	104.5 ± 1.6	143.6 ± 1.5	190.6 ± 1.7
		ε''	101.5 ± 2.6	123.9 ± 2.1	176.9 ± 2.5	265.8 ± 2.9	366.9 ± 2.9
	27	ε'	31.2 ± 1.1	32.9 ± 1.2	38.8 ± 1.2	46.6 ± 1.1	57.7 ± 1.1
		ε''	45.9 ± 1.3	55.3 ± 1.5	77.9 ± 1.6	115.2 ± 1.4	158.1 ± 1.3
	40	ε'	26.6 ± 0.5	27.6 ± 0.5	31.6 ± 0.6	36.5 ± 0.5	44.1 ± 0.5
		ε''	33.9 ± 0.6	40.6 ± 0.7	56.8 ± 0.8	83.4 ± 0.7	114.21 ± 0.6
	915	ε'	14.6 ± 0.2	15.0 ± 0.3	16.5 ± 0.9	18.2 ± 0.6	20.1 ± 0.5
		ε''	5.2 ± 0.2	5.4 ± 0.2	6.3 ± 0.8	7.8 ± 0.7	9.52 ± 0.4
	2450	ε'	12.4 ± 0.1	12.9 ± 0.3	14.3 ± 0.7	16.0 ± 0.2	18.8 ± 0.4
		ε''	4.6 ± 0.2	4.78 ± 0.2	5.2 ± 0.3	6.0 ± 0.2	6.9 ± 0.3
	4500	ε'	10.8 ± 0.1	11.4 ± 0.3	12.7 ± 0.4	14.4 ± 0.4	17.1 ± 0.5
		ε''	4.8 ± 0.3	4.87 ± 0.4	5.39 ± 0.2	6.1 ± 0.2	6.9 ± 0.6
Chestnut weevil slurry (62.2% w.b.)	10	ε'	93.1 ± 3.3	107.8 ± 3.5	125.6 ± 3.7	146.6 ± 4.1	159.2 ± 4.3
		ε''	481.3 ± 11.2	541.2 ± 12.9	613.8 ± 14.0	689.4 ± 15.6	763.9 ± 16.1
	27	ε'	53.5 ± 2.1	58.3 ± 2.0	65.5 ± 2.2	68.6 ± 2.1	70.9 ± 2.1
		ε''	183.5 ± 5.4	205.1 ± 5.6	229.2 ± 6.2	253.7 ± 6.7	281.1 ± 6.8
	40	ε'	49.0 ± 2.0	52.7 ± 1.8	57.8 ± 1.8	59.9 ± 1.9	61.2 ± 2.0
		ε''	124.9 ± 3.3	142.4 ± 3.4	163.1 ± 3.8	180.9 ± 3.9	206.7 ± 4.6
	915	ε'	35.1 ± 1.5	37.1 ± 1.6	38.6 ± 1.5	39.4 ± 1.6	39.8 ± 1.6
		ε''	11.0 ± 0.3	11.3 ± 0.3	12.0 ± 0.3	12.2 ± 0.4	13.3 ± 0.4
	2450	ε'	32.4 ± 1.0	34.3 ± 1.0	35.7 ± 1.0	36.5 ± 1.1	37.0 ± 1.1
		ε''	11.9 ± 0.3	11.4 ± 0.3	10.6 ± 0.3	10.6 ± 0.3	9.8 ± 0.3
	4500	ε'	29.8 ± 0.6	31.8 ± 0.6	33.1 ± 0.6	34.1 ± 0.7	34.7 ± 0.7
		ε''	15.7 ± 0.3	14.8 ± 0.4	13.5 ± 0.3	12.7 ± 0.3	11.3 ± 0.3

constants of both chestnut and chestnut weevil at any temperature decreased with increasing frequency. The decrease with increasing frequency was more rapid at lower frequencies (i.e. 100 MHz) than at higher frequencies. The dielectric constants of compressed chestnut flour and chestnut weevil slurry samples increased with temperature at any given frequency over the measured range. To provide solid data for computer simulation in postharvest treatments using radio-frequency and microwave energy, Table 1 lists the dielectric constants and loss factors of compressed chestnut flour with 45.3% moisture content w.b. and the chestnut weevil slurry with 62.2% moisture content w.b. at 27 MHz, 40 MHz, 915 MHz, 2450 MHz and the two extreme frequencies (10 MHz and 4500 MHz).

The temperature-dependent dielectric constants of compressed chestnut flour and chestnut weevil slurry samples at 27 MHz and 915 MHz are shown in Fig. 2. At any given temperature, the dielectric constant of chestnut weevil was higher than that of chestnut. For example, the dielectric constants were 31.2 and 53.5 for chestnut and chestnut weevil at 20 °C and 27 MHz (Fig. 2(a)), and 20.1 and 39.8 at 60 °C and 915 MHz (Fig. 2(b)), respectively. The dielectric constants of the chestnut and chestnut weevil samples increased with increasing temperature between 20 °C and 60 °C. They increased more rapidly with increasing temperature at 27 MHz than at 915 MHz. For example, when the temperature increased from 20 to 60 °C, the dielectric constant of chestnut increased by 16.5 (from 31.2 to 57.7) at 27 MHz and increased by 5.5 (from 14.6 to 20.1) at 915 MHz, respectively. The dielectric constant of chestnut weevil increased by 17.4 (from 53.5 to 70.9) and 4.7 (from 35.1 to 39.8) at 27 MHz and 915 MHz, respectively. The increased dielectric constant with increasing temperature at a given frequency was also been found in legume flour at 20–90 °C (Guo et al., 2008b, 2010a) and at 20–60 °C (Jiao, Johnson, Tang, Tiwari, & Wang, 2011), and cowpea weevil (Jiao et al., 2011) between 10 and 1800 MHz.

3.2. *Dielectric loss factors*

The log–log plot of measured dielectric loss factors of compressed chestnut flour and chestnut weevil slurry samples at 20–60 °C and 51 frequencies over the frequency range of 10–4500 MHz is presented in Fig. 3. The dielectric loss factors at selected frequencies are also listed in Table 1. Over

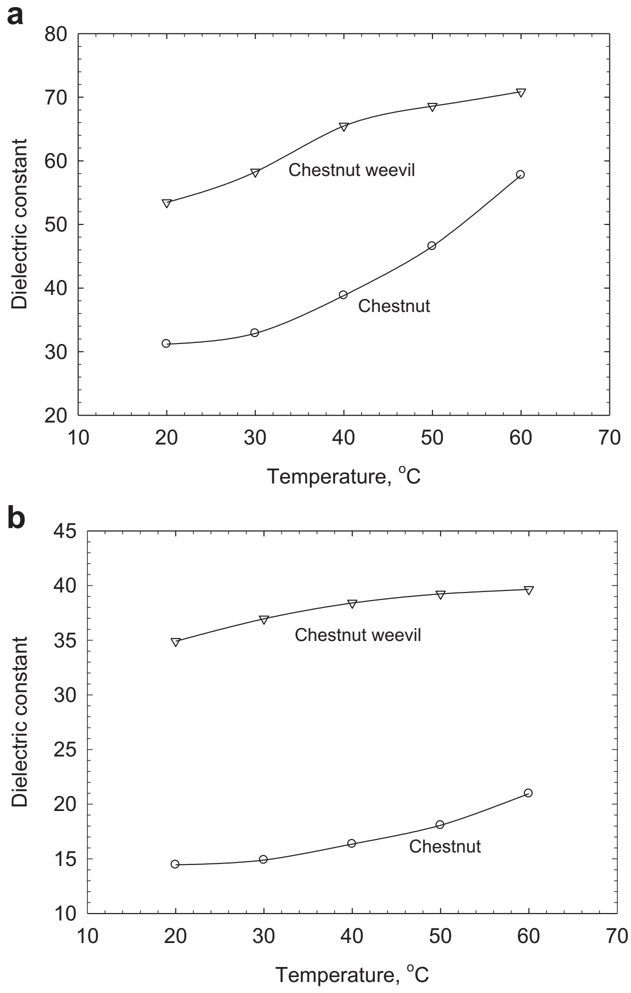

Fig. 2 – Influence of temperature on the dielectric constants of compressed chestnut flour and chestnut weevil slurry at 27 MHz (a) and 915 MHz (b).

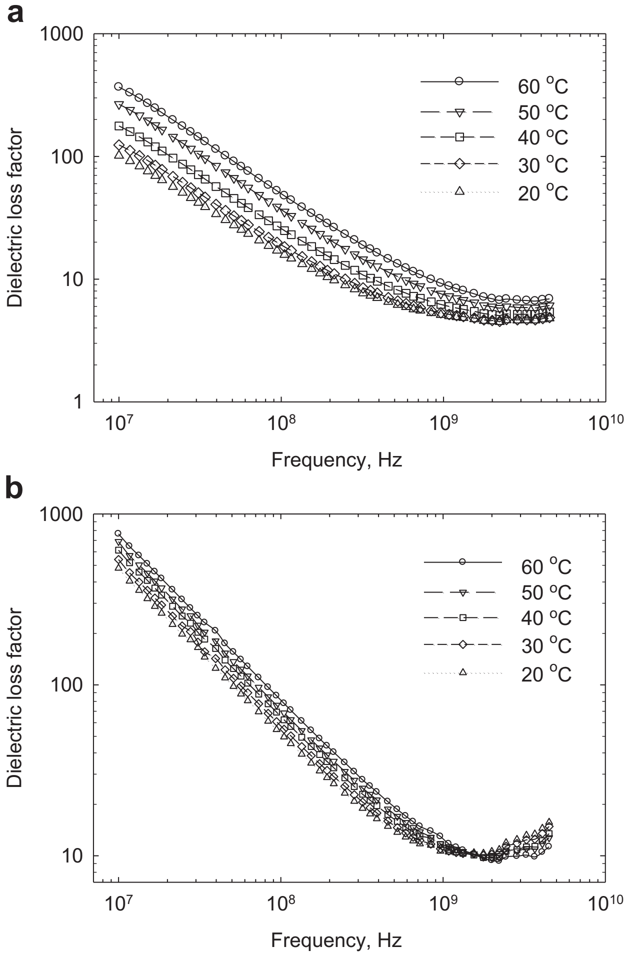

Fig. 3 – Dielectric loss factors of compressed chestnut flour (45.3% w.b.) (a) and chestnut weevil slurry (62.2% w.b.) (b) at indicated temperatures and 51 frequencies from 10 to 4500 MHz.

the investigated frequency range, the dielectric loss factor of compressed chestnut flour samples decreased with increasing frequency below 3000 MHz, but had a slight increase above 3000 MHz (Fig. 3(a)). At a given frequency, the dielectric loss factor of chestnut increased with increasing temperature from 20 to 60 °C.

The dielectric loss factors of the chestnut weevil slurry decreased with increasing frequency to a minimum between 1 and 3 GHz, depending on temperature, and then increased somewhat as frequency increased. The loss factor of chestnut weevil increased with the increase of temperature from 20 to 60 °C below the minimum, whereas it decreased with temperature above that point (Fig. 3(b)). The trend of dielectric loss factor increasing with temperature at similar radio frequencies was also reported in insect pest of fruits (Wang et al., 2003b, 2005), cowpea weevils (Jiao et al., 2011), rice weevils (Nelson et al., 1997), and many moist food materials (Nelson, 2003). The phenomenon of dielectric loss factor decreasing with increasing temperature at microwave frequencies has also been found for rice weevils and other stored-grain insects (Nelson et al., 1998).

With both chestnut and chestnut weevil, and at temperatures between 20 and 60 °C, there is an obvious negative linear relationship between the log of dielectric loss factor and the log of frequency below 300 MHz. The dominant dielectric loss mechanisms at radio or microwave frequencies of practical importance for industrial dielectric heating of moist materials are ionic conduction and dipole relaxation (Ryynänen, 1995). Several studies have demonstrated that ionic conductivity is the dominant loss mechanism at lower frequencies, whereas dipole relaxation plays the major role at microwave frequencies, including those with fish (Wang, Tang, Rasco, Kong, & Wang, 2008), fruit (Guo, Nelson, Trabelsi, & Kays, 2008a, 2011b), milk (Guo et al., 2010b) and egg (Wang, Tang, Wang, & Swanson, 2009).

The dielectric loss factors of compressed chestnut flour and chestnut weevil slurry samples over the frequency range from 10 to 4500 MHz at 20 °C are compared in Fig. 4. The normal dielectric loss factor instead of the log value was used on the vertical axis so as to clearly explore the loss factor differences between chestnut and chestnut weevil at each frequency. The loss factors were 45.9 and 183.5 for compressed chestnut and chestnut weevil at 27 MHz, and 5.2 and 11.0 at 915 MHz at 20 °C, respectively (Fig. 4). The higher the dielectric loss factor, the more power absorbed by materials. The weevil would absorb much more energy, and reach a higher temperature than the chestnut under the same treatment time. This enables the insects to reach lethal temperatures while their hosts are still at lower temperatures, which does not cause heat damage and degrade the quality and appearance of the dielectric heated chestnuts.

The influence of temperature on the dielectric loss factors of compressed chestnut flour and chestnut weevil slurry samples at 27 MHz and 915 MHz is shown in Fig. 5. The chestnut and chestnut weevil at higher temperatures had larger dielectric loss factors than at lower temperatures, which causes the chestnut to absorb more energy at higher temperatures and results in heating non-uniformity.

The larger the ratio of the dielectric loss factor of chestnut weevil to that of chestnuts the better the potential for larger temperature differences to occur between chestnut weevil and chestnut when subjected to dielectric heating (Wang et al., 2003a). The ratio value was 4.0 at 27 MHz, whereas it

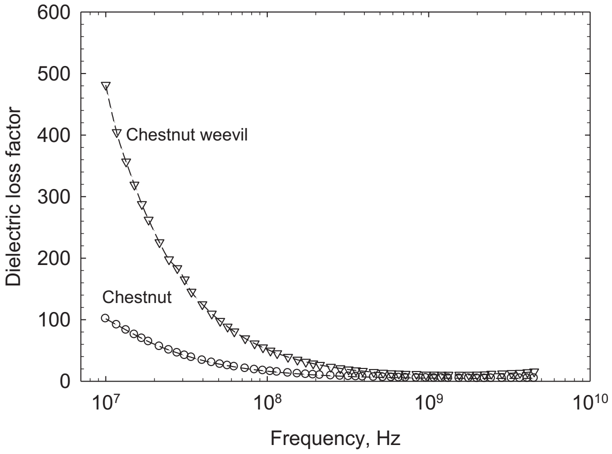

Fig. 4 – Comparison of dielectric loss factors of compressed chestnut flour and chestnut weevil slurry samples from 10 to 4500 MHz at 20 °C.

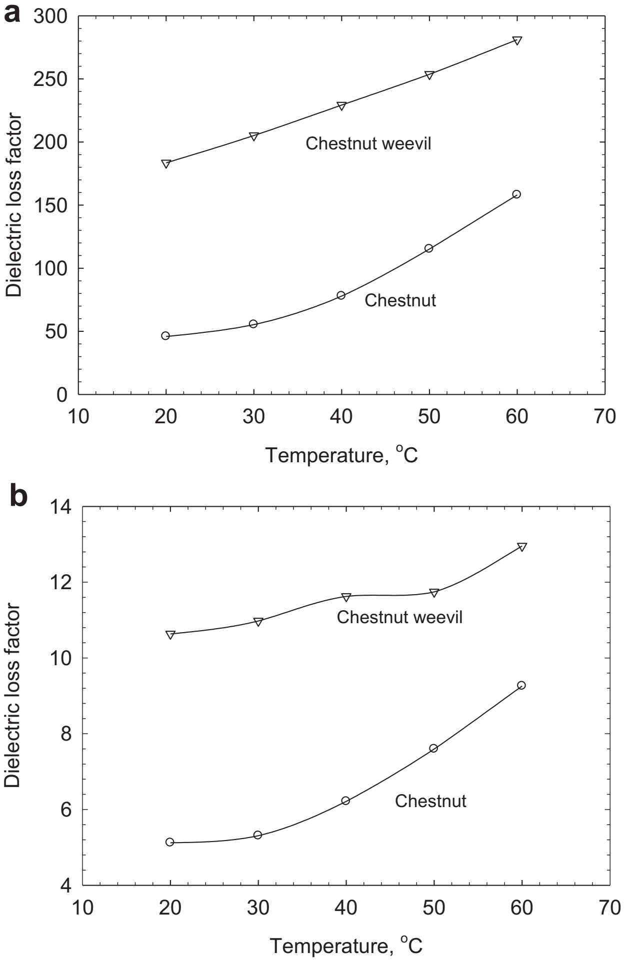

Fig. 5 – Influence of temperature on the dielectric loss factors of compressed chestnut flour and chestnut weevil slurry samples at 27 MHz (a) and 915 MHz (b).

Table 2 – The ratio of the dielectric loss factor of chestnut weevil slurry to compressed chestnut flour at the four frequencies of interest and five temperatures.

Frequency, MHz	Temperature, °C				
	20	30	40	50	60
27	4.0	3.7	2.9	2.2	1.8
40	3.5	3.5	2.9	2.2	1.8
915	2.1	2.1	1.9	1.6	1.4
2450	2.6	2.4	2.0	1.8	1.4

was only 2.1 at 915 MHz at 20 °C. The ratios were 1.8 and 1.4 at 27 MHz and 915 MHz at 60 °C, respectively (Table 2). These loss factor ratio data suggested that the differential heating of the chestnut weevil in fresh chestnut could be possible in radio-frequency treatments at lower frequencies but are unlikely in microwave frequency heating. The distinct advantage of lower frequencies between 10 and 100 MHz over microwave frequencies for selective heating of insects in grain was reported some time ago (Nelson & Charity, 1972; Nelson & Stetson, 1974).

3.3. *Penetration depth*

The calculated penetration depths from dielectric constants and loss factors of compressed chestnut flour samples (45.3% w.b.) at 20 °C, 40 °C and 60 °C between 10 and 4500 MHz are shown in Fig. 6. Penetration depth decreased with increasing frequency. For example, the depths for chestnut were 247 mm at 27 MHz, and 37 mm at 915 MHz at 20 °C. The increasing temperature reduced the penetration depth, especially at lower frequencies. When the temperature increased from 20 °C to 60 °C, the depth at 27 MHz was reduced from 247 mm to 116 mm. The effect of frequency and temperature became small above 1000 MHz where penetration depth became very small.

For uniform and effective control of insect pests with dielectric heating, the thickness of food material should be not more than two or three times the penetration depth (Schiffmann, 1995). Considering the influence of temperature on penetration depth, that thickness is less than 490 mm at 27 MHz, and less than 60 mm at 915 MHz. The penetration depth further indicates dielectric heating treatments below 100 MHz might be the practical choice in developing industrial-scale disinfestation technology for chestnuts.

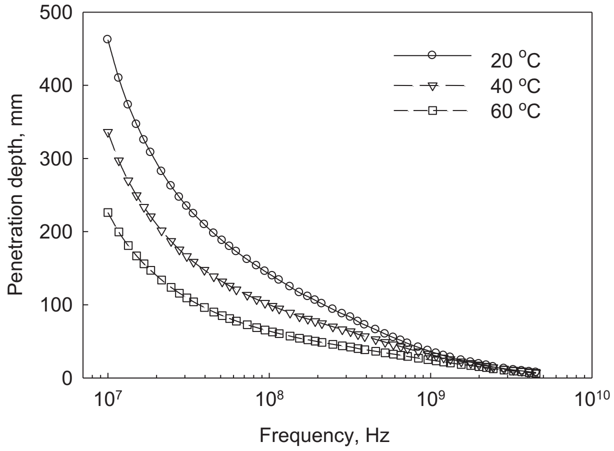

Fig. 6 – The calculated penetration depths of compressed chestnut flour at indicated temperatures from dielectric constants and loss factors in Figs. 1 and 2.

4. Conclusions

The dielectric properties of compressed chestnut flour and chestnut weevil slurry samples were dependent on frequency and temperature. The dielectric constants of chestnut and chestnut weevil decreased with increasing frequency over the frequency range of 10–4500 MHz. The minimum loss factors of chestnut and chestnut weevil were observed at about 3000 MHz and 1000 MHz, respectively. At a given temperature, the loss factor of chestnut weevil was much higher than that of chestnut below 100 MHz.

The temperature between 20 and 60 °C had positive effect on dielectric constant of chestnut and chestnut weevil and loss factor of chestnut over the whole investigated frequency range. The loss factor of chestnut weevil was influenced by temperature positively below about 1000 MHz and negatively above 1000 MHz. A positive influence on loss factor will cause heating non-uniformity.

The penetration depth decreased with increasing frequency and temperature. The potential selective heating for chestnut weevil and deep penetration depth indicated that heating between 10 and 100 MHz might be more practical in controlling insect pests in chestnuts than microwave heating.

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