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Research Paper

Dielectric properties of cowpea weevil, black-eyed peas and mung beans with respect to the development of radio frequency heat treatments

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In developing radio frequency (RF) and microwave (MW) disinfestation treatments for chickpeas and lentils, large amounts of product infested with cowpea weevil must be treated to validate treatment efficacy. To accomplish this, black-eyed peas and mung beans are being considered for use as surrogate host legumes, since they are better hosts for cowpea weevil when compared with the target legumes. Dielectric properties are very important parameters for developing RF and MW treatments and may be used to estimate heating uniformity and penetration depth. Dielectric properties of black-eyed pea and mung bean flours at four moisture content levels as well as cowpea weevil immature stages and adults were measured with an open-ended coaxial probe and impedance analyser at frequencies of 10–1800 MHz and temperatures of 20–60 °C. For both insect and legume samples, the dielectric constant and loss factor decreased with increasing frequency but increased with increasing temperature and moisture content. Comparison of the dielectric loss factor of insects with that for legumes at commonly used industrial frequencies of 27 (RF) and 915 (MW) MHz showed that cowpea weevils should differentially heat faster than the legumes, with the differential heating reduced in MW heating when compared to RF heating. Penetration depths calculated for black-eyed peas and mung beans suggested that RF treatment had much larger penetration depth than MW treatment, and continuous industrial-scale RF treatment protocols could be developed to disinfest these products.

1. Introduction

The United States produces around 1 million metric tonnes of dry peas (*Pisum sativum*), lentils (*Lens culinaris*) and chickpeas (*Cicer arietinum*) each year, and exports of these products bring more than US$90 million into the US economy (USDA-ERS, 2006). These products may be infested with the cowpea weevil, *Callosobruchus maculatus*, a serious pest of many legumes (Arbogast, 1991). Although the cowpea weevil is a cosmopolitan pest, most importing countries require that incoming product be free of the insects. To meet such requirements, producers use chemical fumigants such as methyl bromide or phosphine. Regulatory actions against methyl bromide (UNEP, 2006) and insect resistance to

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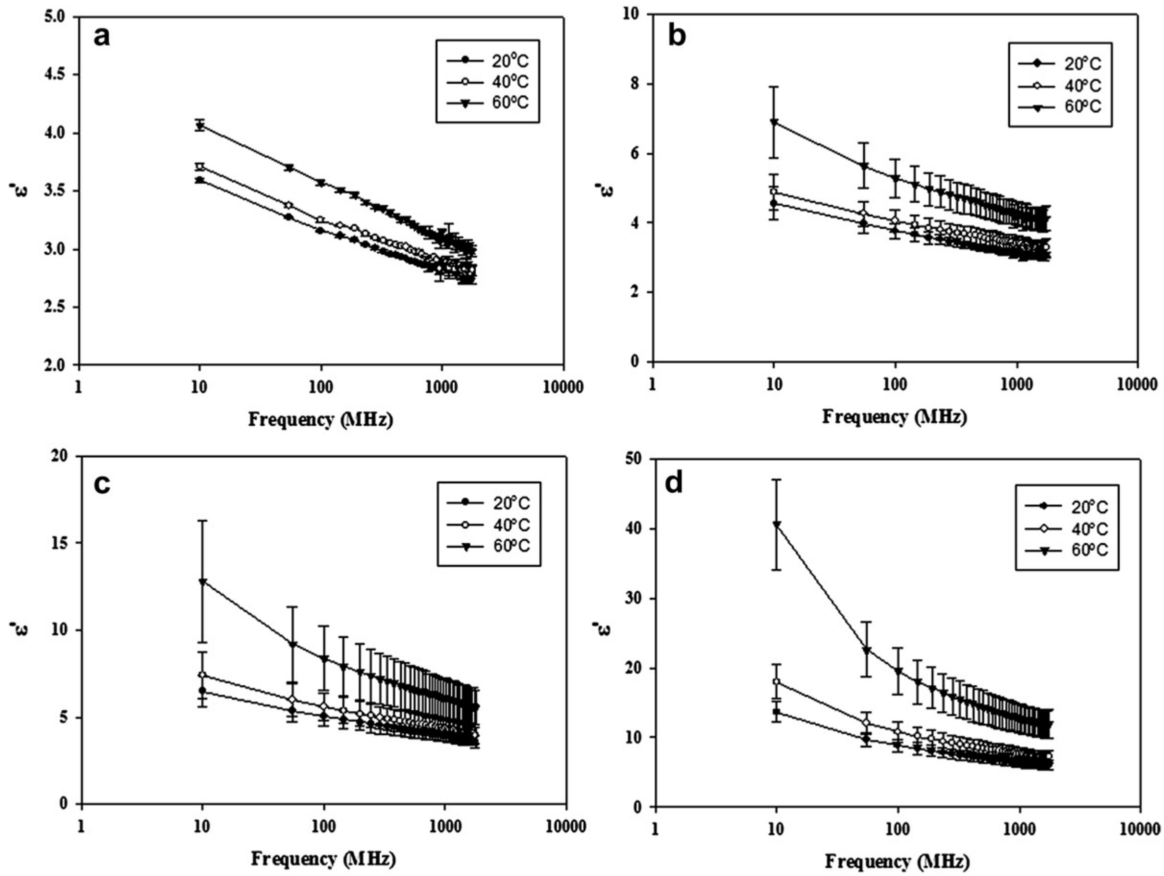

Fig. 1 – Dielectric constant of black-eyed peas as a function of frequencies and temperatures at the moisture content of 8.8 (a), 12.7 (b), 16.8 (c), and 20.9 (d) % w.b.

phosphine (Benhalima, Chaudhry, Mills, & Price, 2004) may make these fumigants costly or unavailable to pea, lentil and chickpea processors. In addition, as the organic industry expands, the need for non-chemical postharvest insect control methods increases (CCOF, 2008). Such concerns over resistance, regulatory actions and the needs of the organic industry have generated a renewed interest in developing non-chemical alternative treatments.

One possible non-chemical alternative is the use of radio frequency (RF) energy to volumetrically heat product (Tang, Ikediala, Wang, Hansen, & Cavalieri, 2000). RF heating is very rapid, significantly reducing treatment times when compared with conventional heating methods. Commercially available RF equipment is currently used for numerous industrial applications, including heating of crackers, yarn and paper (Piyasena, Dussault, Koutchma, Ramaswamy, & Awash, 2003). Many studies have explored using RF energy to disinfest postharvest products of insect pests (Hallman & Sharp, 1994; Nelson, 1996; Nelson, Bartley, & Lawrence, 1998). More recent laboratory studies have shown RF treatments to be effective for control of lesser grain borers in rough rice (Lagunas-Solar et al., 2007), and for codling moth (Wang et al., 2001) and navel orangeworm (Mitcham et al., 2004; Wang, Tang, Johnson, & Hansen, 2002) in in-shell walnuts. Pilot-scale RF treatments were shown to effectively disinfest in-shell walnuts of navel orangeworm under industrial settings with no damage to product quality (Wang, Monzon, Johnson, Mitcham, & Tang, 2007a; Wang, Monzon, Johnson, Mitcham, & Tang, 2007b).

Cowpea weevil has been observed in most legumes, including both chickpeas and lentils (Arbogast, 1991), but some varieties of chickpeas are very poor hosts for cowpea weevil (Ahmed, Khalique, Afzal, Tahir, & Malik, 1989), and lentils are not preferred by ovipositing females (Islam, Akhter, Laz, & Parween, 2007). Our preliminary tests showed that both black-eyed pea (*Vigna unguiculata*) and mung bean (*Vigna radiata*) were good host beans to support cowpea weevil development, as also observed by Arbogast (1991). Because of the poor oviposition on chickpeas and lentils, we selected black-eyed peas and mung beans, similar in size to chickpeas and lentils, respectively, as surrogate hosts in future RF validation tests. Black-eyed peas and mung beans are also economically valuable products that may benefit from RF treatments.

In RF treatments, electromagnetic energy interacts directly with commodities containing polar molecules and charged ions to generate heat. The way in which any material interacts with electromagnetic energy may be described by their dielectric properties. The knowledge of the dielectric properties of both pest insects and products is useful in developing RF treatment protocols. Permittivity describes the dielectric properties that influence RF heating of target products, and the relative complex permittivity ε can be expressed through the following equation:

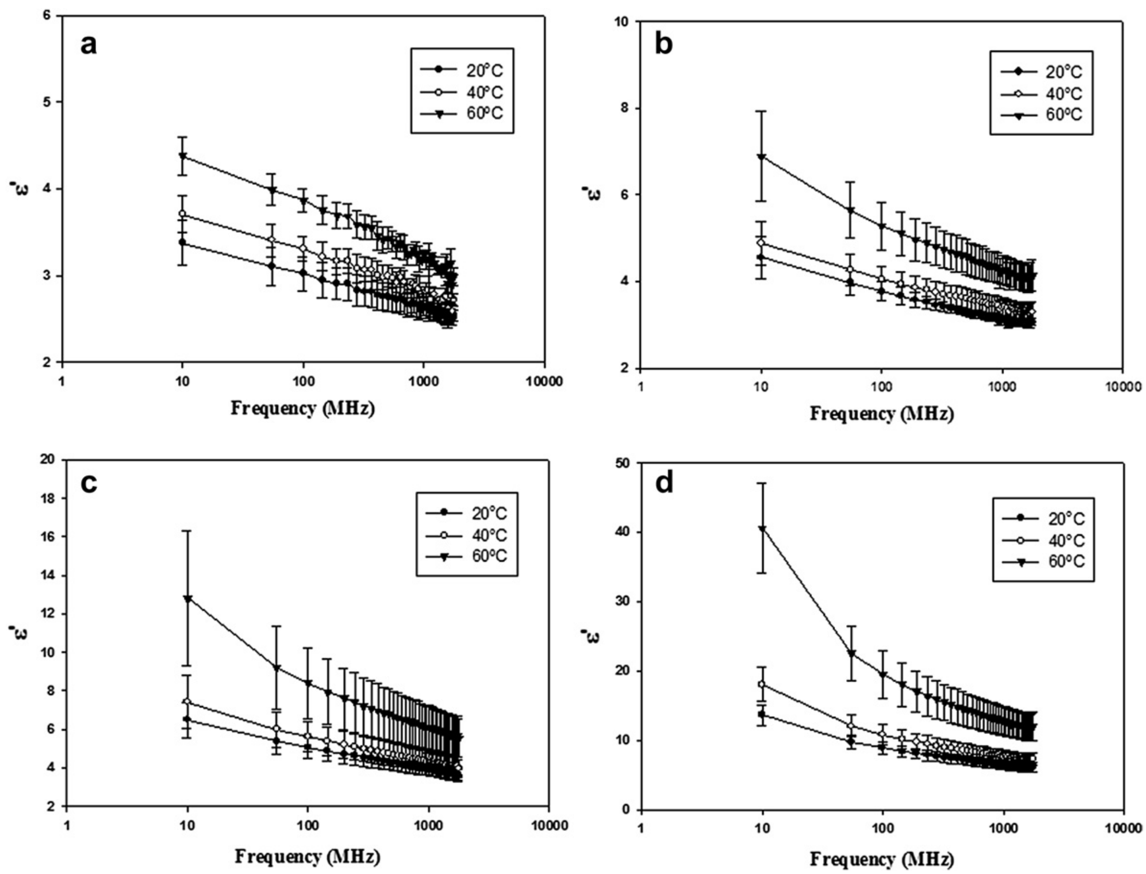

Fig. 2 – Dielectric constant of mung bean as a function of frequencies and temperatures at the moisture content of 10.2 (a), 14.4 (b), 18.2 (c) and 22.3 (d) % w.b.

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

The real part ε' is the dielectric constant and represents stored energy when the material is exposed to an electric field. The imaginary part ε'' is the dielectric loss factor, reflecting the materials ability to dissipate electrical energy as heat, and $j = \sqrt{-1}$ (Mudgett, 1994). Dielectric properties directly influence the conversion of the energy from the electromagnetic field into heat, which can be expressed as:

$$\rho C_P \frac{\Delta T}{\Delta t} = 5.56 \times 10^{-11} f E^2 \varepsilon'' \tag{2}$$

where C_P is the specific heat of the material in J (kg °C)$^{-1}$, ρ is the density of the material in kg m^{-3}, ΔT is the temperature rise in the material in °C, Δt is the time duration in s, f is frequency (Hz), and E is electric field intensity (V m^{-1}) (Nelson, 1996). From Eq. (2) it can be seen that the rise in temperature is proportional to the dielectric loss factor, in addition to electric field intensity (squared), frequency and treatment time.

Several comprehensive reviews on dielectric properties of numerous foods and agricultural products are available (Foster & Schwan, 1989; Marra, Zhang, & Lyng, 2009; Nelson, 1973, 1991, 2008; Ryynänen, 1995; Sosa-Morales, Valerio-Junco, López-Malo, & García, 2010). Dielectric properties have been reported for different frequency ranges, temperatures and moisture contents for a variety of dry products (Berbert, Queriroz, & Melo, 2002; Berbert et al., 2001; Guo, Tiwari, Tang, & Wang, 2008; Guo, Wang, Tiwari, Johnson, & Tang, 2010; Lawrence, Nelson, & Kraszewski, 1990; Nelson, 1984; Nelson, 2005; Nelson & Trabelsi, 2006; Trabelsi, Kraszewski, & Nelson, 1998; Sacilik, Tarimci, & Colak, 2006). Factors such as frequency, temperature, salt content, moisture content and the state of moisture (frozen, free or bound) influence the dielectric properties of biological materials. In developing RF disinfestation treatments, dielectric studies are useful in calculating penetration depth of the product, important information in the engineering design and calculation of throughput.

Limited reports are available on dielectric properties of insects such as grain weevils (Nelson & Payne, 1982), potato beetles (Colpitts, Pelletier, & Cogswell, 1992), and woodworms (Andreuccetti, Bini, Ignesti, Gambetta, & Olmi, 1994). Ikediala, Tang, Drake, and Neven (2000) reported dielectric properties of four apple cultivars and codling moth larvae in a relatively high frequency range (30–3000 MHz). Wang et al. (2005) and Wang, Tang, Johnson, et al. (2003) measured the dielectric properties of eight important postharvest pest species along with targeted host agricultural commodities. Comparing the dielectric properties of pest insects and target products is also useful, and often indicates that high moisture insects absorb more energy than low moisture products, resulting in differential heating of the insects in a dry host (Wang, Tang, Cavalieri, & Davis, 2003).

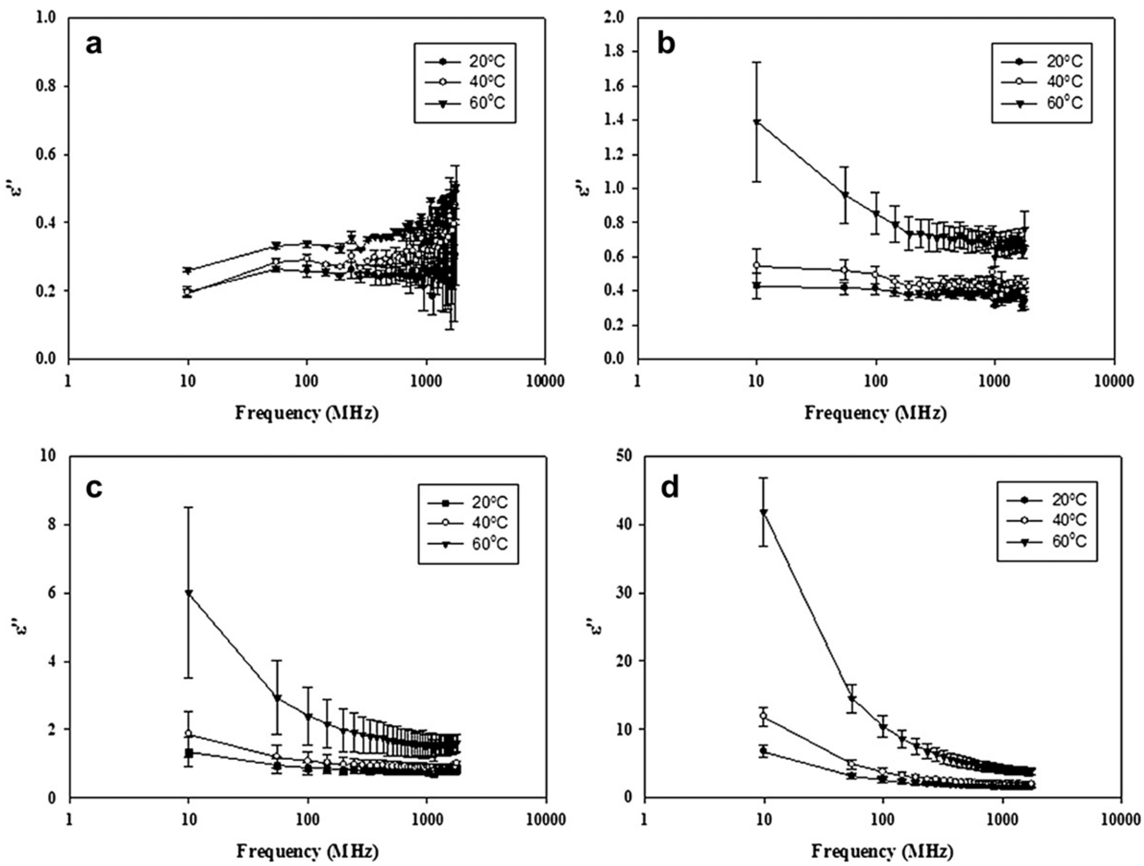

Fig. 3 – Dielectric loss factor of black-eyed peas as a function of frequencies and temperatures at the moisture content of 8.8 (a), 12.7 (b), 16.8 (c), and 20.9 (d) % w.b.

The objectives of this research were (1) to measure dielectric properties of the cowpea weevil and the proposed surrogate legumes, black-eyed peas and mung beans, (2) to determine the effects of frequency (10–1800 MHz), temperature (20–60 °C) and moisture content on these properties, (3) to compare the loss factor of cowpea weevil with that of the two surrogate legumes and other targeted legumes at 27 and 915 MHz, and (4) to determine the penetration depth of electromagnetic energy into those commodities at 27, 40 and 915 MHz, frequencies commonly used in industrial heating applications.

2. Materials and methods

2.1. *Insect and bean samples*

Cowpea weevils were obtained from the San Joaquin Valley Agricultural Sciences Center (SJVASC) Insectary laboratory culture originally isolated from black-eyed peas near Patterson, CA in 1999 (SJVASC Insectary, 2007). The culture was maintained on black-eyed peas at 28 ± 0.5 °C and a photoperiod of 14 h light and 10 h dark. Black-eyed peas were purchased from Pacific Grain & Foods, Fresno, CA, USA; and mung beans from Living Whole Foods, Inc., Springville, UT, USA. The initial moisture contents of black-eyed pea and mung bean were 8.8, and 10.2% wet basis (w.b.), respectively.

2.2. *Sample preparation and measurements of moisture content and true density*

To prepare insect samples for dielectric properties measurements, mature larvae and pupae were carefully dissected from infested black-eyed peas and stored in a freezer at −20 °C. Adult weevils were also collected from culture jars and stored at −20 °C. Samples were then packed in insulated containers and shipped overnight to Washington State University (Pullman, WA). To homogenise the samples and minimise the air gaps among samples during dielectric property measurement, insects were ground into slurries with a mortar and pestle. About 30 cm^3 of slurry was used in dielectric measurements for each sample. Dielectric properties measurement of insects was conducted immediately after blending to minimise degradation of the haemolymph and other constituents (Ikediala et al., 2000; Wang et al., 2005). The initial moisture content of the insect slurry was estimated by weighing and then drying three 2–3 g subsamples in a hot air oven at 60 °C for three days. After drying, the samples were re-weighed to calculate moisture content. Samples were weighed precisely to nearest 0.0001 g using an analytical balance (OHAUS Co., NJ, USA). Samples were placed inside the closed glass cabinet of analytical balance to avoid the effect of air movement and buoyancy.

The liquid displacement method was used to measure true density for black-eyed pea and mung bean. Toluene ($C_6H_5CH_3$)

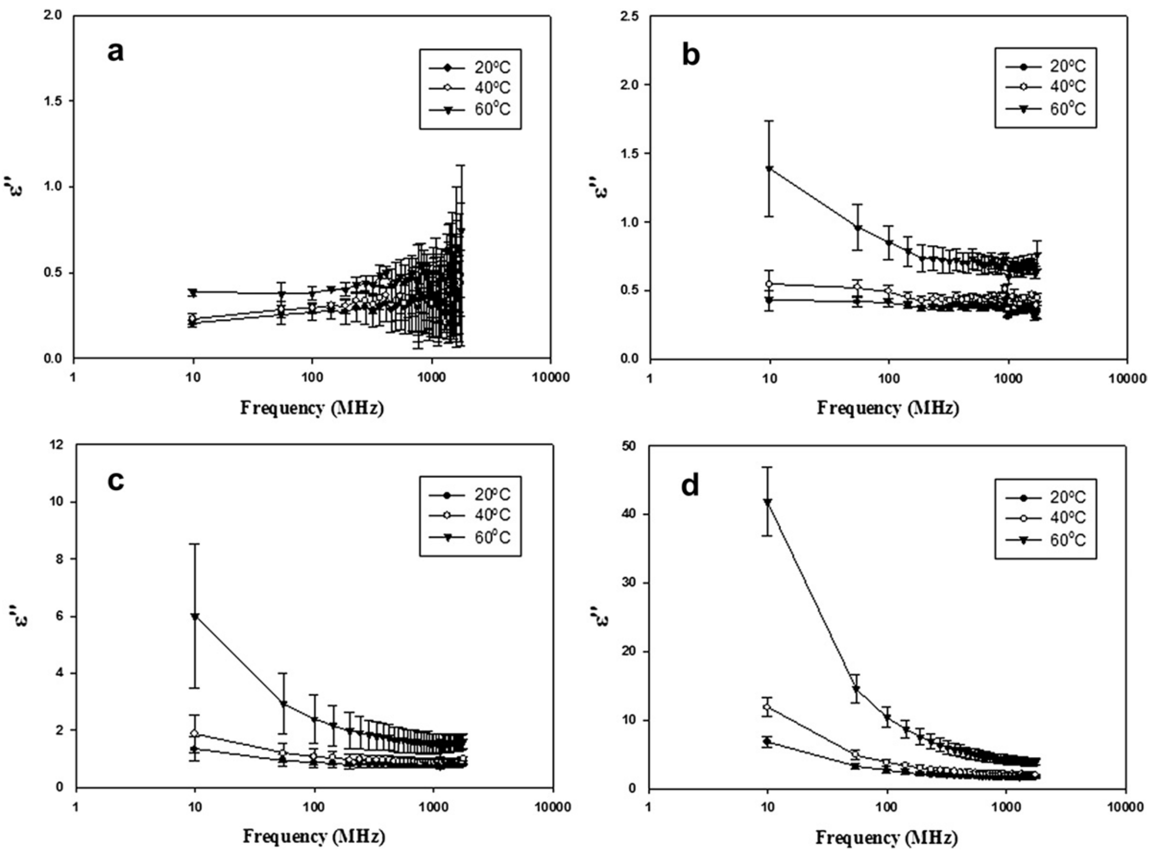

Fig. 4 – Dielectric loss factor of mung bean as a function of frequencies and temperatures at the moisture content of 10.2 (a), 14.4 (b), 18.2 (c) and 22.3 (d) % w.b.

was used as a displacement liquid due to its stable specific gravity and viscosity, and low tendency to permeate through the sample (Guo et al., 2010). The true density of black-eyed pea and mung bean were measured at four different moisture content levels (black-eye pea: 8.8, 12.8, 16.8 and 20.8% w.b.; mung bean: 10.2, 14.2, 18.2 and 22.2% w.b.). Measurements were replicated thrice for each sample and mean true densities were calculated and used for subsequent dielectric properties measurement. The detailed measurement procedures and results can be found in Jiao, Tang, Johnson, Tiwari, and Wang (2011).

Irregularly shaped legume particles do not make good contact with the small flat probe surface for accurate measurements, so compressed pellets made of homogeneous legume flour conditioned to specific moisture contents were used in dielectric properties measurement. Legumes were first ground to flour in a coffee grinder. A specific weight of flour was uniformly distributed on filter paper held above distilled water in a desiccator for varying lengths of time. Moisture content of the flour was measured by placing 2–3 g samples in aluminium dishes and drying them in a vacuum oven (ADP-31, Yamato Scientific America Inc., Santa Clara, CA, USA) for 1 h at 130 °C and 75–85 kPa (AOAC, 2002). Samples were placed in desiccators with $CaSO_4$ until they reached room temperature and then weighed. Measurements were replicated three times.

After the desired moisture contents were reached, the flours were compressed in a cylindrical mould (2 cm diam. × 3 cm high) using a hydraulic press (Fred S. Carver Inc. Summit, NJ, USA). Because dielectric properties of particulate materials are influenced by sample density (Berbert et al., 2002), flours were compressed as described by Guo et al. (2008) to the true density previously derived for each legume.

2.3. *Dielectric properties measurement*

The dielectric properties of insect and legume samples were measured using an open-ended coaxial-line probe connected to an impedance analyser (HP4291B, Hewlett Packard Corp., Santa Clara, CA, USA). To obtain uniform readings, the measurement system was turned on and kept in a standby condition for about 30 min before calibration. After the impedance analyser had been calibrated with an open, short, low loss capacitance, and 50 Ω load, the open-ended coaxial-line probe was calibrated with air, short-circuit, and deionised water at 25 °C. A personal computer with software (85070D, Agilent Technologies, Inc., Santa Clara, CA, USA) was used to control the system and record data. The impedance analyser cable and probe were maintained in a fixed position during calibration and measurement to minimise measurement errors. Before and after each measurement, the probe and the sample cell were cleaned with deionised water and wiped dry.

After following the standard calibration procedure for the impedance analyser, dielectric properties of cowpea weevil immature stages and adults, and legume samples at four moisture content levels were determined over frequencies of

Table 1 – Dielectric property data (mean ± STD) of black-eyed pea and mung bean at five temperatures and three frequencies.

Materials	Moisture content (w.b.)	Temp. (°C)	Dielectric constant			Dielectric loss factor		
			Frequency (MHz)			Frequency (MHz)		
			27	40	915	27	40	915
Black-eyed pea	8.8%	20	3.40 ± 0.02	3.33 ± 0.01	2.84 ± 0.02	0.24 ± 0.02	0.26 ± 0.02	0.24 ± 0.09
		30	3.43 ± 0.01	3.36 ± 0.01	2.86 ± 0.02	0.25 ± 0.02	0.26 ± 0.02	0.26 ± 0.07
		40	3.51 ± 0.01	3.44 ± 0.01	2.88 ± 0.02	0.27 ± 0.02	0.28 ± 0.02	0.34 ± 0.07
		50	3.62 ± 0.01	3.56 ± 0.02	2.96 ± 0.02	0.28 ± 0.03	0.29 ± 0.02	0.34 ± 0.09
		60	3.84 ± 0.02	3.77 ± 0.02	3.08 ± 0.02	0.31 ± 0.01	0.33 ± 0.01	0.42 ± 0.02
	12.7%	20	3.60 ± 0.04	3.50 ± 0.04	2.88 ± 0.05	0.33 ± 0.03	0.34 ± 0.03	0.28 ± 0.03
		30	3.75 ± 0.03	3.64 ± 0.01	2.94 ± 0.03	0.38 ± 0.01	0.38 ± 0.03	0.30 ± 0.03
		40	4.07 ± 0.04	3.95 ± 0.04	3.13 ± 0.06	0.47 ± 0.01	0.47 ± 0.02	0.35 ± 0.05
		50	4.59 ± 0.09	4.43 ± 0.08	3.43 ± 0.03	0.64 ± 0.03	0.62 ± 0.02	0.46 ± 0.05
		60	5.50 ± 0.18	5.27 ± 0.16	3.87 ± 0.03	0.97 ± 0.09	0.92 ± 0.06	0.62 ± 0.03
	16.8%	20	3.64 ± 0.06	3.54 ± 0.06	2.86 ± 0.06	0.40 ± 0.06	0.39 ± 0.04	0.40 ± 0.02
		30	3.82 ± 0.02	3.71 ± 0.02	2.95 ± 0.05	0.47 ± 0.07	0.45 ± 0.04	0.44 ± 0.01
		40	4.18 ± 0.06	4.04 ± 0.06	3.26 ± 0.06	0.60 ± 0.07	0.55 ± 0.05	0.48 ± 0.02
		50	4.98 ± 0.12	4.78 ± 0.12	3.57 ± 0.04	0.91 ± 0.14	0.83 ± 0.11	0.66 ± 0.03
		60	6.67 ± 0.53	6.32 ± 0.47	4.39 ± 0.22	1.67 ± 0.36	1.50 ± 0.29	0.94 ± 0.09
	20.9%	20	8.90 ± 0.45	8.36 ± 0.37	5.45 ± 0.10	2.44 ± 0.12	2.17 ± 0.09	1.31 ± 0.05
		30	9.50 ± 0.75	9.97 ± 0.74	5.51 ± 0.02	2.65 ± 0.16	2.37 ± 0.16	1.35 ± 0.01
		40	9.86 ± 0.41	9.23 ± 0.36	5.86 ± 0.12	3.06 ± 0.17	2.68 ± 0.13	1.46 ± 0.06
		50	11.22 ± 0.56	10.47 ± 0.54	6.40 ± 0.08	3.94 ± 0.14	3.41 ± 0.13	1.66 ± 0.03
		60	13.86 ± 0.77	12.78 ± 0.66	7.62 ± 0.35	6.06 ± 0.32	5.10 ± 0.26	2.08 ± 0.05
Mung bean	10.2%	20	3.23 ± 0.23	3.15 ± 0.23	2.61 ± 0.15	0.23 ± 0.03	0.24 ± 0.05	0.34 ± 0.20
		30	3.38 ± 0.20	3.31 ± 0.20	2.71 ± 0.13	0.24 ± 0.04	0.26 ± 0.04	0.36 ± 0.17
		40	3.53 ± 0.19	3.45 ± 0.19	2.80 ± 0.10	0.26 ± 0.04	0.27 ± 0.04	0.36 ± 0.15
		50	3.75 ± 0.17	3.66 ± 0.17	2.91 ± 0.10	0.28 ± 0.04	0.30 ± 0.04	0.39 ± 0.13
		60	4.15 ± 0.19	4.05 ± 0.19	3.13 ± 0.11	0.37 ± 0.05	0.38 ± 0.05	0.46 ± 0.16
	14.4%	20	4.21 ± 0.37	4.07 ± 0.31	3.15 ± 0.06	0.43 ± 0.04	0.42 ± 0.04	0.43 ± 0.02
		30	4.15 ± 0.24	4.03 ± 0.22	3.25 ± 0.12	0.47 ± 0.07	0.45 ± 0.06	0.41 ± 0.02
		40	4.50 ± 0.41	4.37 ± 0.41	3.47 ± 0.20	0.54 ± 0.07	0.52 ± 0.07	0.51 ± 0.04
		50	5.17 ± 0.66	5.00 ± 0.66	3.84 ± 0.31	0.75 ± 0.15	0.69 ± 0.12	0.59 ± 0.04
		60	6.07 ± 0.75	5.83 ± 0.75	4.34 ± 0.35	1.11 ± 0.22	1.01 ± 0.18	0.73 ± 0.06
	18.2%	20	5.77 ± 0.73	5.53 ± 0.67	4.01 ± 0.37	1.06 ± 0.28	0.99 ± 0.25	0.79 ± 0.10
		30	5.88 ± 0.74	5.64 ± 0.69	4.06 ± 0.37	1.10 ± 0.29	1.02 ± 0.25	0.80 ± 0.08
		40	6.48 ± 1.05	6.19 ± 0.96	4.37 ± 0.53	1.40 ± 0.44	1.27 ± 0.38	0.91 ± 0.14
		50	7.88 ± 1.64	7.45 ± 1.50	5.03 ± 0.76	2.18 ± 0.80	1.92 ± 0.67	1.17 ± 0.23
		60	10.36 ± 2.57	9.66 ± 2.30	6.11 ± 1.15	3.81 ± 1.48	3.26 ± 1.23	1.57 ± 0.41
	22.3%	20	10.98 ± 1.18	10.23 ± 1.08	6.58 ± 0.60	4.16 ± 0.51	3.57 ± 0.44	1.65 ± 0.17
		30	11.56 ± 1.22	10.74 ± 1.12	6.83 ± 0.61	4.64 ± 0.50	3.94 ± 0.43	1.72 ± 0.13
		40	13.83 ± 1.86	12.73 ± 1.70	7.86 ± 0.94	6.75 ± 0.87	5.60 ± 0.74	2.12 ± 0.25
		50	18.92 ± 3.16	17.14 ± 2.86	9.88 ± 1.46	11.83 ± 1.73	9.57 ± 1.42	2.94 ± 0.45
		60	27.50 ± 4.71	24.46 ± 4.23	13.01 ± 2.08	21.80 ± 2.86	17.28 ± 2.38	4.34 ± 0.73

10–1800 MHz and temperatures of 20–60 °C. The temperature range was determined by the thermal death kinetic studies of cowpea weevil, which showed that less than 10 min exposure time at 58 °C was needed to achieve 100% mortality of all cowpea weevil life stages (Johnson, Wang, & Tang, 2010). Detailed information about the dielectric property measurement system and procedure can be found elsewhere (Guo et al., 2008, 2010; Wang, Tang, Johnson, et al., 2003b). The measurements were replicated twice.

To explore possible differential heating, dielectric loss factors were compared for cowpea weevil stages (immatures and adult) and high moisture legumes (black-eyed pea, mung bean, chickpea and lentil at 20.9, 22.9, 20.9 and 21.5% w.b., respectively) at 27 and 915 MHz. These frequencies were chosen because they are commonly used in industrial RF (27 MHz) and MW (915 MHz) heating applications.

2.4. Penetration depth calculation

Penetration depth of RF and MW power is defined as the depth at which the power is reduced to $1/e$ ($e = 2.718$) of the power at the surface. The penetration depth d_p in m for RF and MW energy in a material can be calculated according to von Hippel (1954):

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

where c is the speed of light in free space (3×10^8 m s^{-1}). After obtaining the dielectric properties, the penetration depths of electromagnetic energy into the two legume samples were calculated at three frequencies (27, 40, and 915 MHz), five temperatures (20, 30, 40, 50 and 60 °C) and all four moisture contents.

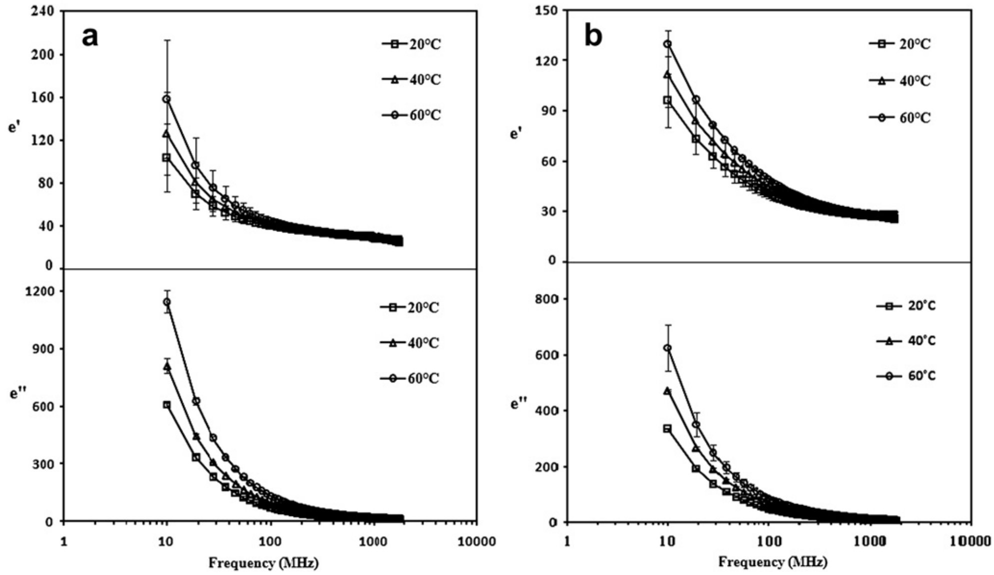

Fig. 5 – Dielectric constant and loss factor of (a) cowpea weevil immature stages and (b) cowpea weevil adults as a function of frequency and temperature.

3. Results and discussion

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

The semi-log plot of the dielectric constant at different frequencies is presented for compressed flour samples of black-eyed peas (Fig. 1) and mung beans (Fig. 2) over temperatures of 20–60 °C at different moisture contents. Generally, the dielectric constant increased with decreasing frequency and increasing temperature and moisture content for both legumes. Corresponding plots for dielectric loss factor are shown in Figs. 3 and 4 for black-eyed peas and mung beans, respectively. Like the dielectric constant, the dielectric loss factor for both legumes also increased with increasing temperature and moisture content, while it decreased with increasing frequency, especially at the higher moisture contents. This trend was not apparent for the lowest moisture content, 8.8 and 10.2% w.b. for black-eyed peas and mung beans, respectively. The negative relationship between dielectric loss factor and frequency was most evident at high

Table 2 – Dielectric constant (ε') and loss factor (ε'') of cowpea weevil and other insects reported in the literature at room temperatures.

Insects	Life Stage	Frequency (MHz)						Reference
		40		200		915		
		ε'	ε''	ε'	ε''	ε'	ε''	
Rice weevil	Adult	–	–	55	48	46	19	Nelson et al. (1998)
Colorado potato beetle	Adult	–	–	53	81	–	–	Nelson (2004)
Red flour beetle	Adult	–	–	61	56	52	20	Nelson et al. (1998)
Sawtoothed grain beetle	Adult	–	–	70	68	60	25	Nelson et al. (1998)
Lesser grain borer	Adult	–	–	63	72	54	23	Nelson et al. (1998)
Codling moth	Fifth instar larvae	–	–	68	72	60	21	Ikediala et al. (2000)
Codling moth	Fifth instar larvae	65	163	56	40	48	12	Wang, Tang, Cavalieri, et al. (2003); Wang, Tang, Johnson, et al. (2003)
Indian-meal moth	Fifth instar larvae	69	149	46	35	40	13	Wang, Tang, Cavalieri, et al. (2003); Wang, Tang, Johnson, et al. (2003)
Mexican fruit fly	Third instar larvae	71	231	50	58	49	18	Wang, Tang, Cavalieri, et al. (2003); Wang, Tang, Johnson, et al. (2003)
Navel orange worm	Fifth instar larvae	69	213	52	50	45	16	Wang, Tang, Cavalieri, et al. (2003); Wang, Tang, Johnson, et al. (2003)
Cowpea weevil	Larvae and pupae	50	168	36	40	30	15	This study
Cowpea weevil	Adult	55	104	34	29	28	10	This study

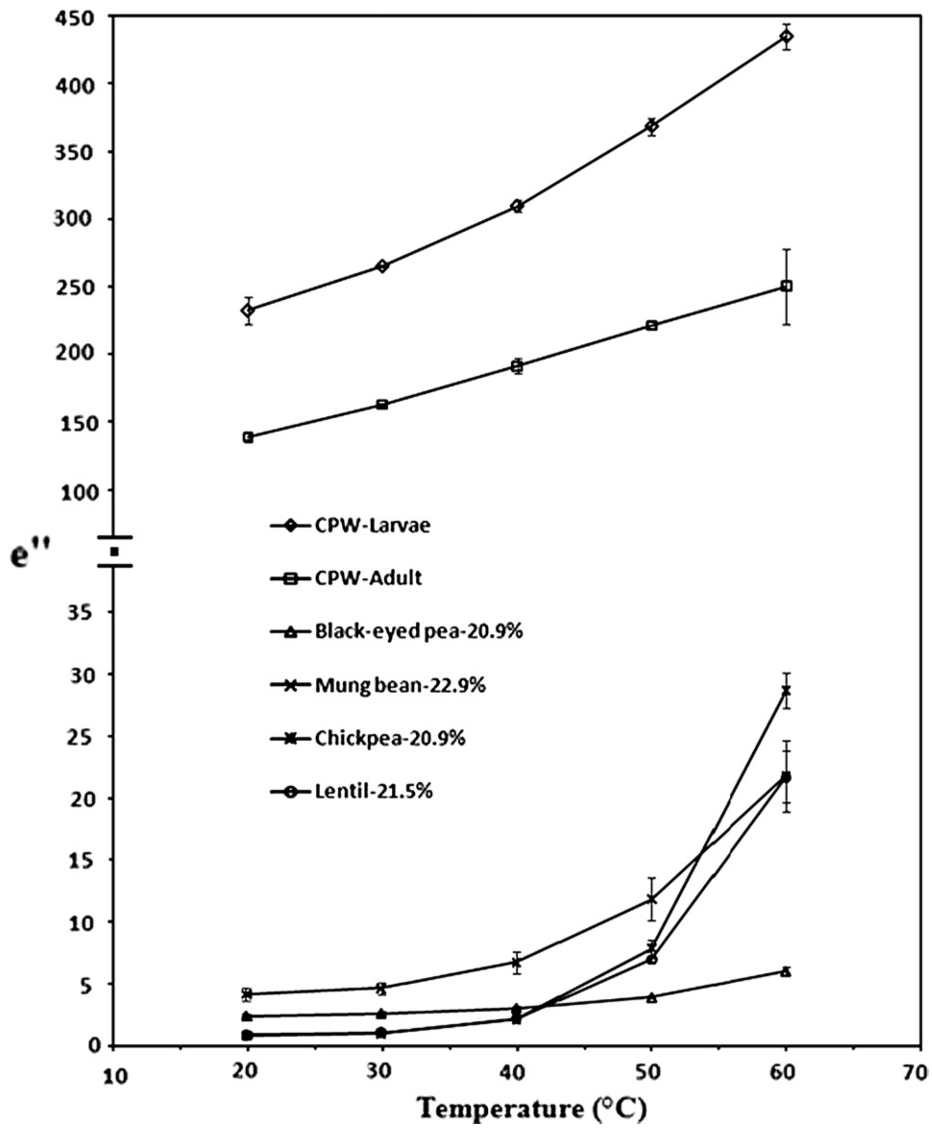

Fig. 6 – Dielectric loss factor at the frequency of 27 MHz as a function of temperature at high moisture contents for four types of legumes compared with that of cowpea weevil immature stages and adults (data for chickpea and lentil were adapted from Guo et al. (2008, 2010)).

temperatures, high moistures and low frequencies. Guo et al. (2010) reported a similar relationship for chickpea, green pea, lentil and soybean, suggesting that this was because the ionic conductance played a dominant role under these conditions when the effect of dipole rotation was negligible. This phenomenon has also been found in high moisture foods, fresh fruits, and vegetables (Guan, Cheng, Wang, & Tang, 2004; Guo, Nelson, Trabelsi, & Kays, 2007; Guo et al., 2008; Nelson, 2005; Wang et al., 2005; Wang, Tang, Rasco, Kong, & Wang, 2008). For both dielectric constant and loss factor of black-eyed pea and mung bean at high frequencies especially at low moisture levels, the variation seemed larger than at low frequencies and high moisture levels. Similar results were observed in the other four legumes (Guo et al., 2008, 2010), and were probably caused by system error and calibration noise. Although it is ideal for liquid or semi-solid samples, the coaxial probe method could result in some variations of dielectric properties in solid samples, especially at low moisture levels. Dielectric properties of black-eyed pea and mung bean flours at five temperatures and three commonly used frequencies are showed in Table 1.

The dielectric property values of black-eyed pea and mung bean are comparable and of the same order of magnitude as those of the other four legumes (chickpea, lentil, green pea and soybean) reported by Guo et al. (2008, 2010) using the same technique. The frequency-dependent dielectric properties of the two legume flours are similar to those of wheat flour in the same frequency range (Nelson & Trabelsi, 2006) and of wheat kernel (Lawrence et al., 1990) between 0.1 and 100 MHz.

Dielectric constants and loss factors for cowpea weevil immature stages (larvae and pupae) and adults are given in Fig. 5. Dielectric constants of cowpea weevils were very similar for immature stages and adults, and decreased with increasing frequency and decreasing temperature. The effect of temperature on the dielectric constants was most apparent

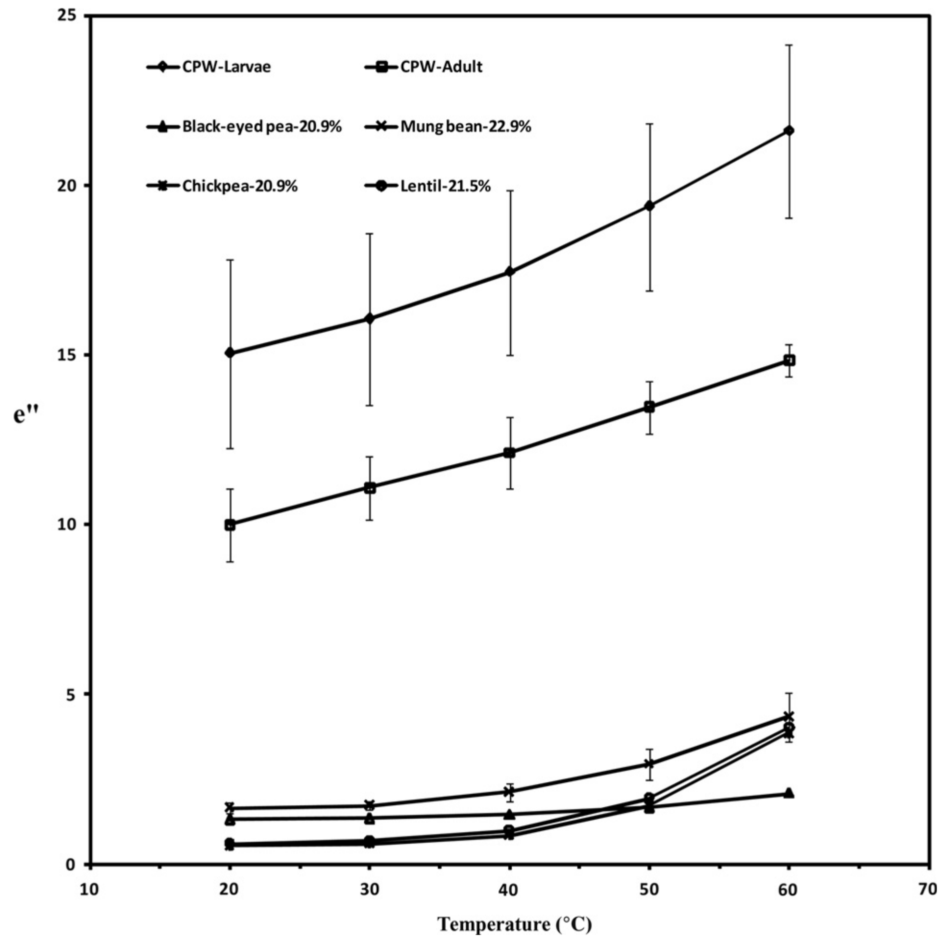

Fig. 7 – Dielectric loss factor at the frequency of 915 MHz as a function of temperature at high moisture contents for four types of legumes compared with that of cowpea weevil immature stages and adults (data for chickpea and lentil were adapted from Guo et al. (2008, 2010)).

at lower frequencies. Dielectric loss factor for both cowpea weevil stages also decreased with increasing frequency and decreasing temperature. Ikediala et al. (2000) reported a similar trend for the dielectric properties of codling moth larvae and Wang, Tang, Johnson, et al. (2003) found comparable results for four kinds of common fruit insects. The loss factor for immature cowpea weevils was higher than that for adults. This was probably due to the higher moisture content in immature stages (70.8% w.b.) than in adults (43.9% w.b.).

Table 2 summarises the dielectric properties of various insect life stages at room temperature and three common frequencies. Dielectric properties of stored product insects were lower than those of insects in fresh fruits at low frequencies (e.g. 40 MHz), probably caused by the higher moisture contents of the latter insects. But these differences were reduced at high frequencies (e.g. 915 MHz). Ikediala et al. (2000) reported that the dielectric properties of slurries of fifth instar codling moth larvae were about 20% higher than those of whole insects, which is probably due to better contact between the probe and slurry samples, and higher density of insect slurries. The density-dependent dielectric behaviour of whole insects was also confirmed by Nelson et al. (1998).

3.2. *Comparison of dielectric loss factor between insects and legumes*

A comparison of dielectric loss factor between insects and legumes is shown in Figs. 6 and 7 for 27 and 915 MHz, respectively, as a function of temperature. At both frequencies, the dielectric loss factor of black-eyed pea and mung bean was of the same order of magnitude as for the two legumes reported by Guo et al. (2008, 2010). But dielectric loss factor for cowpea weevils was clearly higher than that for all legumes, even at relatively high moisture contents, and the difference increased with increasing temperature. This suggests differential heating between insects and dried legumes will occur, resulting in higher insect temperatures and increased efficacy while lower legume temperatures will preserve good product quality. The difference in dielectric loss factor between cowpea weevils and legumes at 27 MHz was much higher than that at 915 MHz, indicating the differential heating was most likely to happen in RF systems. Similar findings have also been observed between codling moth larvae and in-shell walnuts during RF heating (Wang, Tang, Cavalieri, et al., 2003).

Table 3 – The calculated penetration depths of black-eyed pea and mung bean at the three selected frequencies over four moisture contents and five temperatures.

Material	Moisture content (% w.b.)	Frequency (MHz)	Penetration depths (cm)				
			Temperature (°C)				
			20	30	40	50	60
Black-eyed pea	8.8	27	1340 ± 122	1326 ± 148	1233 ± 128	1216 ± 154	1109 ± 51
		40	844 ± 65	830 ± 66	791 ± 73	777 ± 59	704 ± 19
		915	38 ± 11	32 ± 13	30 ± 3	29 ± 8	26 ± 4
	12.7	27	1008 ± 89	901 ± 15	766 ± 19	696 ± 34	431 ± 50
		40	651 ± 61	598 ± 44	504 ± 23	405 ± 14	300 ± 25
		915	31 ± 4	30 ± 3	27 ± 5	21 ± 3	17 ± 1
	16.8	27	842 ± 151	740 ± 131	603 ± 88	433 ± 82	276 ± 90
		40	583 ± 79	515 ± 50	434 ± 47	314 ± 52	201 ± 58
		915	22 ± 2	20 ± 1	19 ± 1	15 ± 1	11 ± 1
	20.9	27	218 ± 17	208 ± 21	184 ± 14	153 ± 9	111 ± 9
		40	160 ± 10	152 ± 17	137 ± 10	115 ± 7	85 ± 7
		915	9 ± 0	9 ± 0	9 ± 0	8 ± 0	7 ± 0
Mung bean	10.2	27	1375 ± 131	1330 ± 146	1263 ± 132	1205 ± 126	976 ± 103
		40	870 ± 138	834 ± 118	813 ± 102	762 ± 97	640 ± 79
		915	25 ± 9	23 ± 7	25 ± 7	23 ± 5	20 ± 5
	14.4	27	844 ± 44	768 ± 77	693 ± 56	536 ± 59	393 ± 46
		40	574 ± 33	530 ± 49	479 ± 56	385 ± 38	287 ± 30
		915	21 ± 1	23 ± 1	19 ± 2	17 ± 2	15 ± 2
	18.2	27	403 ± 63	392 ± 61	324 ± 58	230 ± 44	152 ± 29
		40	286 ± 44	279 ± 41	234 ± 41	171 ± 32	115 ± 22
		915	13 ± 2	13 ± 2	12 ± 3	10 ± 3	8 ± 4
	22.3	27	143 ± 27	132 ± 22	100 ± 21	68 ± 16	45 ± 10
		40	109 ± 21	101 ± 18	78 ± 17	53 ± 13	36 ± 8
		915	8 ± 1	8 ± 1	7 ± 1	6 ± 1	4 ± 1

3.3. *Penetration depth*

Penetration depths calculated from the measured dielectric properties of black-eyed peas and mung beans at three specific frequencies over five temperatures and four moisture contents are listed in Table 3. Penetration depth decreased with increasing frequency, temperature and moisture content, which was in good agreement with the values reported for chickpeas, green peas, lentils and soybeans (Guo et al., 2010). When compared with those of lentils at similar moisture levels, penetration depths for black-eyed peas were lower at 20 °C but higher at 60 °C. A similar trend was observed when the penetration depths for mung beans were compared to those of green pea. Moisture content had a large effect on penetration depths, with the highest moisture contents resulting in the least penetration depth. The penetration depths were the greatest at 27 MHz, a common frequency used for industrial RF applications, ranging from 1340 to 111 cm for black-eyed peas and from 1375 to 45 cm for mung beans. In contrast, at 915 MHz, a common industrial MW frequency, the penetration depth for both legumes was much lower (<40 cm), which limits the design of treatments to relatively thin product layers. Since the sample depth for the proposed treatment will be around 10 cm (Wang, Tiwari, Jiao, Johnson, & Tang, 2010), the slight differences in penetration depths between the two surrogate legumes and their target legumes at 27 MHz should not bias the results of subsequent efficacy studies. Also, the penetration depths of black-eyed peas and mung beans suggest that a uniform and continuous RF treatment could be developed for commercial disinfestation of these products.

4. Conclusions

Our current study determined dielectric property data for black-eyed peas and mung beans, legumes that are better hosts for cowpea weevils than the target legumes (chickpeas and lentils), as well as for cowpea weevil immature stages and adults. Dielectric constant and loss factor of both insect and legume samples decreased with increasing frequency and increased with increasing temperature and moisture content. Our results also showed that there could be differential heating between cowpea weevils and legumes during RF treatment, since the dielectric loss factor of cowpea weevils was much higher than that of legumes at 27 MHz even at relatively high moisture content. This differential heating should be less pronounced at the industrial MW frequency (915 MHz) when compared to the industrial RF frequency (27 MHz) according to the measured dielectric loss factor. Penetration depths calculated for black-eyed peas and mung beans suggest that industrial RF heating systems could be used to disinfest large quantities of these products.

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