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Frequency, moisture and temperature-dependent dielectric properties of chickpea flour

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Knowledge of dielectric properties of agricultural commodities is essential to develop thermal treatments using radio frequency and microwave energy. Dielectric properties (the dielectric constant and loss factor) of compressed chickpea flour samples were determined using an open-ended coaxial-line probe with an impedance analyzer over the frequency range from 10 to 1800 MHz, moisture contents from 7.9% to 20.9% w.b., and temperatures from 20 to 90 °C. Both dielectric constant and loss factor of chickpea samples decreased monotonically with increases in frequency at all temperatures and moisture levels. Ionic conduction was the dominant factor influencing the dielectric loss at lower frequencies in relatively high moisture samples. Dielectric constant and loss factor increased with increases in temperature and moisture content. The rate of increase was greater at higher temperature and moisture levels than at lower temperature and moisture levels. A linear relationship was obtained between the dielectric constant and loss factor when divided by the sample density. Knowledge of the frequency, moisture, and temperature-dependent behaviours of chickpea samples should be helpful in dielectric heating applications and developing new dielectric property based moisture meters.

1. Introduction

Chickpea (*Cicer arietinum*) is one of the most important legumes. It is a good source of folate, rich in protein and high in dietary fibre, thus an excellent source of healthy food. India contributes 75% of the total world production of chickpea followed by Turkey and Pakistan (Singh *et al.*, 2004). Chickpea is an important rotational pulse crop in the United States; its production reached 69,870 metric tons in 2006 with a value of about US$38 millions. Washington state produced 24,380 metric tons of chickpea, valued at US$11.1 millions in 2006 (USDA-NASS, 2007). About 31% of chickpea produced in the USA is exported to India, Korea, Spain, and Latin American countries (USDA-FAS, 2007). To meet quarantine regulations for international trade of chickpea, there is an increased interest in developing effective postharvest pest control using microwave (MW) and radio frequency (RF) energy (Wang *et al.*, 2001, 2002, 2006b, 2007a,b; Mitcham *et al.*, 2004). Knowledge of dielectric properties is important to understand the interaction between chickpea and electromagnetic field.

The dielectric properties include the dielectric constant ε' and loss factor ε'', real and imaginary parts of relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$. The dielectric constant is associated with the ability of a material to store electrical energy in the

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presence of an external electric field, whereas the loss factor refers to the dissipation of energy in the form of losses; *i.e.*, a reflection of a material's ability to convert electromagnetic energy to thermal energy (Nelson, 1973). The mechanisms that contribute to the dielectric loss in heterogeneous mixtures include polar, electronic, atomic and Maxwell-Wagner responses (Metaxas and Meredith, 1993).

Since the first data on the dielectric parameters of grain published in 1953 (Nelson *et al.*, 1953), numerous studies have been reported on dielectric properties of agro-products, such as grain seeds or grain flours (Nelson, 1983, 1984; Trabelsi *et al.*, 1998; Nelson and Trabelsi, 2006), fruits and vegetables (Ikediala *et al.*, 2000; Wang *et al.*, 2003b; Nelson, 2005b; Guo *et al.*, 2007; Nelson *et al.*, 2007). Abegaonkar *et al.* (1999, 2003) correlated the changes in the resonance frequency of a microstrip ring resonator around 10.27 GHz as a non-invasive moisture sensor for chickpea kernels. But there has been no published report on dielectric properties of chickpea flour or kernels at RF and MW frequencies relevant to industrial heating applications.

Many factors, including frequency, temperature and moisture content, influence the dielectric properties of agro-products and food materials (Nelson, 1965, 1981; Ryynänen, 1995; Içier and Baysal, 2004; Venkatesh and Raghavan, 2004). Knowledge of the relationship between frequency and dielectric properties is helpful in determining the optimum frequency range in which the material in question has the desired dielectric characteristics for intended applications (Nelson and Payne, 1982; Wang *et al.*, 2001; Nelson, 2005a; Wang *et al.*, 2006a). The moisture-dependent dielectric properties in specific frequency ranges can be used to develop on-line moisture meters (Nelson et al., 1992), which may be applied not only in drying processes but also in other unit operations in the food industry (Nelson, 1984; Berbert *et al.*, 2002). The purpose of this research was to study frequency (10–1800 MHz), moisture content (7.9–20.9% w.b.) and temperature (20–90 °C) dependent dielectric properties of chickpea flour and kernels for industrial heating and other applications.

2. Materials and methods

2.1. Materials

Seeds of chickpea were purchased from a local grocery store in Pullman, Washington, USA. Fifty seeds were randomly selected to measure average seed length, width, and thickness. Measurement was performed by choosing three orthogonally oriented directions in a single seed. The average and standard deviation (SD) dimensions of 50 chickpea seeds were 10.44 ± 0.45 mm in length, 8.34 ± 0.30 mm in width, and 7.89 ± 0.36 mm in thickness, respectively. The sample compositions determined with standard methods are summarized in Table 1.

2.2. Sample preparation

Open-ended coaxial-line probe technology is best suited for measuring the dielectric properties of homogeneous liquids and soft semi-solids (Hewlett–Packard, 2005). This method requires close contact between the flat tip of the probe and the sample. Chickpea kernels have irregular shapes, and it is impossible to measure directly the dielectric properties of intact chickpea seeds with this method. Therefore, homogeneous samples of desired geometry were prepared by compressing chickpea flour.

Table 1 – Chickpea seed compositions and methods used in measurement

Compositions	Amount	Methods
Ash (%)	3.12	AOAC 920.181
Calories (Kcal (100 g)$^{-1}$)	386.1	CFR 101.9
Carbohydrate (%)	69.3	CFR 101.9
Fat (%)	2.8	AOAC 992.06
Moisture (%)	7.9	AOAC 934.01
Protein (%)	20.9	AOAC 955.04
Sodium (mg (100 g)$^{-1}$)	16	AOAC 975.03

Dielectric properties of particulate materials depend on sample density (Nelson, 1983, 1984; Berbert *et al.*, 2002). In order to obtain accurate dielectric properties data for intact chickpea kernels, a metal cylindrical holder 10 cm in height and 20.7 mm in inner diameter was designed to compress ground chickpea so that the density of the compressed samples matched that of true kernel density. The required amount of ground chickpea for compression was calculated using kernel density and sample height. The samples were then compressed on a hydraulic press to a desired level (about 3 cm in height) in the holder with a flat bottom metal piston.

To obtain the compressed samples of different moisture contents, chickpea kernels (7.9% moisture content, wet basis) were first ground and kept over distilled water in covered desiccators. Ground flours were allowed to absorb moisture in the desiccators at room temperature. The flours were stirred to ensure that moisture was uniformly distributed. After achieving desired moisture contents (after 3–5 days in desiccators), flours were sealed in plastic bags and equilibrated for two days at room temperature. The flours thus prepared for 11.4%, 15.8% and 20.9% w.b. were then compressed to make homogeneous samples.

2.3. Measurement of kernel density

To prepare the samples with the desired density at each moisture content, it was necessary to determine the density of chickpea seeds. Samples of about 200 g whole chickpea (moisture content 7.9% on wet basis) were placed in plastic bags and appropriate amounts of distilled water were added to raise the moisture content to desired levels (12%, 16% and 20% on wet basis). The bags were sealed, shaken to distribute water and stored at 4 °C for four days in an incubator. During storage, bags were shaken several times per day to achieve uniform moisture distribution. Four days later, samples were taken from the incubator and allowed to equilibrate at room temperature for one more day.

The liquid displacement method was used to measure chickpea kernel density at different moisture contents. Toluene (C_7H_8) was used as the immersion liquid, instead of water, to avoid absorption by the samples. Toluene also fills shallow dips in a seed due to its low surface tension (Öğüt, 1998). Kernel density was determined by dividing the weight of randomly selected samples (~25 g) by the volume occupied by those kernels as measured with toluene in 100 ml pycnometers. For each moisture content, experiments were replicated three times and the mean density values were calculated from the replicated results.

A regression equation was developed to describe the relationship between moisture content and kernel density of chickpea.

2.4. Moisture content measurement

Moisture content was determined by drying triplicate 2–3 g ground chickpea samples on aluminum moisture dishes at 130 °C for 1 h in a vacuum oven (ADP-31, Yamato Scientific America, Inc., USA). The samples were cooled in a desiccator with $CaSO_4$ at the bottom before reweighing to determine water loss. Moisture content was estimated from the initial and final weights of the samples.

2.5. Dielectric properties measurement

An open-ended coaxial-line probe connected to an impedance analyzer (HP4291B, Hewlett Packard Corp., Santa Clara, CA, USA) with an upper frequency limit of 1800 MHz was used to measure dielectric properties. To obtain uniform readings, the measurement system was turned on and kept in a standby condition for at least 1 h before calibration and measurement. Dielectric property measurements were made on a linear scale from 10 to 1800 MHz. This frequency range covers three U.S. Federal Communication Commission (FCC) allocated RF (13, 27 and 40 MHz) and one MW frequency (915 MHz) for industrial heating applications. The upper frequency (1800 MHz) is close to another FCC allocated frequency 2450 MHz, mainly used in domestic MW ovens. After the impedance analyzer was 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 distilled water at 25 °C. A personal computer and software (85070D, Agilent Technologies, Inc., Santa Clara, CA, USA) were used to control the system and record the measured data. The impedance analyzer cable and probe were maintained at fixed positions during calibration and measurement to minimize errors.

After calibration at room temperature, a compressed sample (about 13 g) was placed in a stainless steel sample cell. About 0.3 g ground chickpea flour was placed on the top of the compressed sample to ensure a good contact with the coaxial probe. The cell was raised to bring the coaxial probe into firm contact with the sample, and the contact was maintained *via* a pressure spring (about 20 N force). The dielectric properties, ε' and ε'', of the compressed chickpea samples were automatically recorded.

Sample temperature was controlled by circulating a solution of 10% water and 90% ethylene glycol through a jacket of the cell from an ethylene glycol bath (model 1157, VWR Scientific Products, Niles, IL, USA). The sample temperature was raised from 20 to 90 °C in 10 °C increments. After each measurement, the water bath was set to the next temperature level. About 10 min was needed for the sample temperature to reach equilibrium. A pre-calibrated type-T thermocouple temperature sensor was used to measure the sample temperature.

For each moisture content level (7.9%, 11.4%, 15.8% and 20.9% w.b.), three replicated measurements were made. Mean values and SDs were calculated from the replicates.

3. Results and discussions

3.1. Moisture dependence of kernel density of chickpea

The kernel density of chickpea decreased from 1.43 to 1.28 g cm^{-3} with increasing moisture content from 7.9% to 20.9% w.b. (Fig. 1). The following equation was used to describe the kernel density, ρ (g cm^{-3}), as the function of moisture content, W (decimal value):

$$\rho = 1.19 + 0.019/W \quad (R^2 = 0.99, 0.079 \leq W \leq 0.209) \tag{1}$$

Konak *et al.* (2002) also noticed a decrease in chickpea kernel density with increases in moisture content from 4.9% to 14.2% w.b. Tang and Sokhansanj (1993) reported a reduction of the kernel density in lentil from 1.45 to 1.40 g cm^{-3} when moisture content increased from 6.1% to 24.0% w.b. Kernel density of lentil seed decreased from 1.27 to 1.21 g cm^{-3} with an increase in moisture content from 10.3% to 21.0% w.b. (Amin *et al.*, 2004). A linear decrease in kernel density with an increase in grain moisture in the range of 8.0–20% w.b. for soybean was also observed by Deshpande *et al.* (1993).

The densities of the compressed chickpea flour samples are listed in Table 2, along with true chickpea kernel densities directly measured or estimated from Eq. (1). The differences were mainly caused by sample relaxation after removal of the compressive force. The lower the moisture content, the more difficult it was to retain the original sample height after the compression. The densities of the compressed samples at 7.9%, 11.4% and 15.8% w.b. were lower than the kernel densities at corresponding moisture contents. But the density

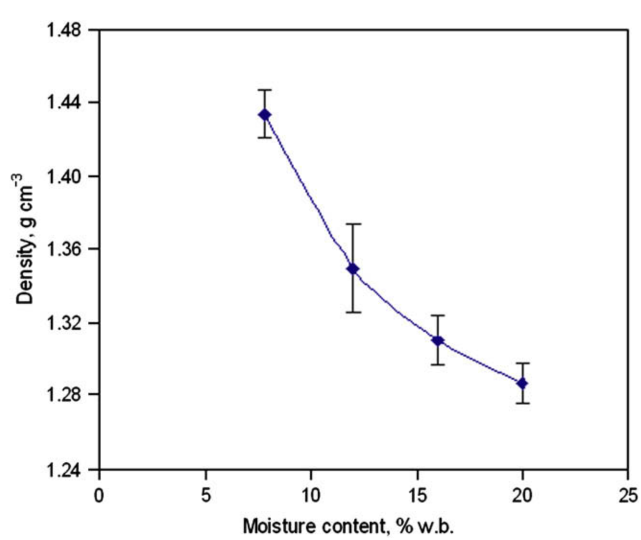

Fig. 1 – Moisture dependence of kernel density of chickpea.

Table 2 – Kernel densities and compressed chickpea sample densities at four moisture contents

Moisture content (%)	Kernel density ($g\,cm^{-3}$)	Compressed sample density ($g\,cm^{-3}$)	Difference (%)
7.9	1.434	1.265 ± 0.026	−11.7
11.4	1.356	1.275 ± 0.001	−6.0
15.8	1.312	1.279 ± 0.002	−2.5
20.9	1.283	1.321 ± 0.007	3.0

of the compressed samples at 20.9% was 3% higher than the kernel density (Table 2).

3.2. *Frequency dependence of dielectric properties of chickpea flour*

Dielectric constant, ε', and loss factor, ε'', of the compressed chickpea samples at different moisture contents are summarized in Tables 3–6. Overall, both the dielectric constant and loss factor were influenced by frequency, especially at high moisture contents. For example, in the studied frequency range, the dielectric constant and loss factor of 20.9% moisture content samples decreased monotonically with increase in frequency at all measured temperatures (Table 6). At elevated temperatures, the effect of frequency on the permittivity was much more pronounced than at room temperature. When the frequency increased from 27 to 1800 MHz, the dielectric constant of 20.9% moisture content samples decreased from 4.50 to 3.12 at 20 °C, but from 71.59 to 23.80 at 90 °C; the loss factor decreased from 0.81 to 0.52 at 20 °C, but from 248.25 to 10.39 at 90 °C.

The results for the frequency dependence of dielectric properties for chickpea flour were similar to those of wheat flour in the same frequency range (Nelson and Trabelsi, 2006) and of wheat kernel (Lawrence *et al.*, 1990) between 0.1 and 100 MHz. The dielectric constant of common beans was found to be decreased as the frequency increased from 0.075 to 5 MHz at all moisture contents. The dependence of the loss factor on frequency was less regular than that of dielectric constant (Berbert *et al.*, 2002).

The dielectric properties of materials are governed by free water dispersion, bound water dispersion, and ionic conduction within a broad frequency range (Feng *et al.*, 2002). When the loss factors of 20.9% moisture content chickpea samples were plotted against frequency in a log–log plot (see Fig. 2a), $\log \varepsilon''$ had negative linear relationship with $\log f$, especially at elevated temperatures in the lower frequency range between 1 and 100 MHz for room temperature and between 1 and 1000 MHz for 90 °C. The negative linear relationship in the log–log plot is a clear indication of the dominant ionic contribution to the dielectric loss mechanisms in bio-materials (Hasted, 1973; Tang, 2005). This phenomenon is typical in high moisture processed foods and fresh fruits, vegetables, and eggs (Guan *et al.*, 2004; Nelson, 2005b; Wang *et al.*, 2005; Guo *et al.*, 2007; Ragni *et al.*, 2007; Wang *et al.*, 2008). In low moisture samples, on the other hand, water as a solvent for charged ions becomes less available, resulting in low loss factor in the RF range (Wang *et al.*, 2003a,b). This is evident in 7.9% moisture content chickpea flour samples, in particular at temperatures between 20 and 70 °C (Fig. 2b).

3.3. *Moisture and temperature dependence of dielectric properties*

To better understand the relationships between permittivity, moisture content and temperature, the dielectric constant and loss factor at 27 MHz were plotted *versus* temperature ranging from 20 to 90 °C at four moisture levels from 7.9% to 20.9% w.b. (Fig. 3, Tables 3–6). This specific frequency is one of five FCC allocated frequencies for industrial, scientific, and medical (ISM) applications. Both ε' and ε'' increased with increasing moisture content at each temperature. Greater increase was observed in dielectric properties when moisture content was above 12%.

Fig. 3 also shows that both ε' and ε'' increased with increasing temperature at all four moisture levels. At low temperatures (below 40 °C) changes in permittivities were very small. A rapid change in permittivity was observed when temperature was raised above 40 °C, especially at higher moisture levels. Nelson and Trabelsi (2006) also noticed an increase in dielectric properties of ground wheat with increases in temperature, and the increase of ε' was more

Table 3 – Dielectric properties (mean ± SD) of compressed chickpea flour with 7.9% moisture content at different temperatures over the frequency range from 10 to 1800 MHz

Frequencies, MHz		20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C	90 °C
27	ε'	2.99 ± 0.01	3.16 ± 0.04	3.23 ± 0.10	3.44 ± 0.10	3.94 ± 0.12	4.86 ± 0.16	6.81 ± 0.17	11.20 ± 0.32
	ε''	0.16 ± 0.01	0.26 ± 0.05	0.16 ± 0.07	0.19 ± 0.04	0.32 ± 0.01	0.58 ± 0.02	1.38 ± 0.11	4.27 ± 0.63
40	ε'	2.90 ± 0.06	3.10 ± 0.05	3.17 ± 0.16	3.29 ± 0.24	3.74 ± 0.25	4.68 ± 0.25	6.45 ± 0.28	10.43 ± 0.34
	ε''	0.20 ± 0.01	0.26 ± 0.03	0.19 ± 0.06	0.14 ± 0.14	0.25 ± 0.11	0.48 ± 0.12	1.21 ± 0.20	3.64 ± 0.52
100	ε'	2.84 ± 0.05	2.93 ± 0.11	3.02 ± 0.15	3.16 ± 0.20	3.60 ± 0.22	4.42 ± 0.21	5.91 ± 0.23	9.09 ± 0.25
	ε''	0.17 ± 0.01	0.23 ± 0.01	0.18 ± 0.05	0.17 ± 0.08	0.25 ± 0.08	0.46 ± 0.08	0.98 ± 0.11	2.53 ± 0.29
915	ε'	2.51 ± 0.03	2.60 ± 0.04	2.67 ± 0.05	2.77 ± 0.10	3.08 ± 0.11	3.64 ± 0.10	4.68 ± 0.13	6.72 ± 0.11
	ε''	0.15 ± 0.04	0.18 ± 0.07	0.18 ± 0.10	0.21 ± 0.12	0.29 ± 0.13	0.47 ± 0.13	0.81 ± 0.12	1.58 ± 0.16
1800	ε'	2.43 ± 0.03	2.47 ± 0.02	2.58 ± 0.04	2.65 ± 0.05	2.97 ± 0.10	3.46 ± 0.07	4.36 ± 0.10	6.19 ± 0.13
	ε''	0.19 ± 0.06	0.17 ± 0.07	0.22 ± 0.10	0.27 ± 0.11	0.37 ± 0.12	0.54 ± 0.11	0.85 ± 0.11	1.54 ± 0.14

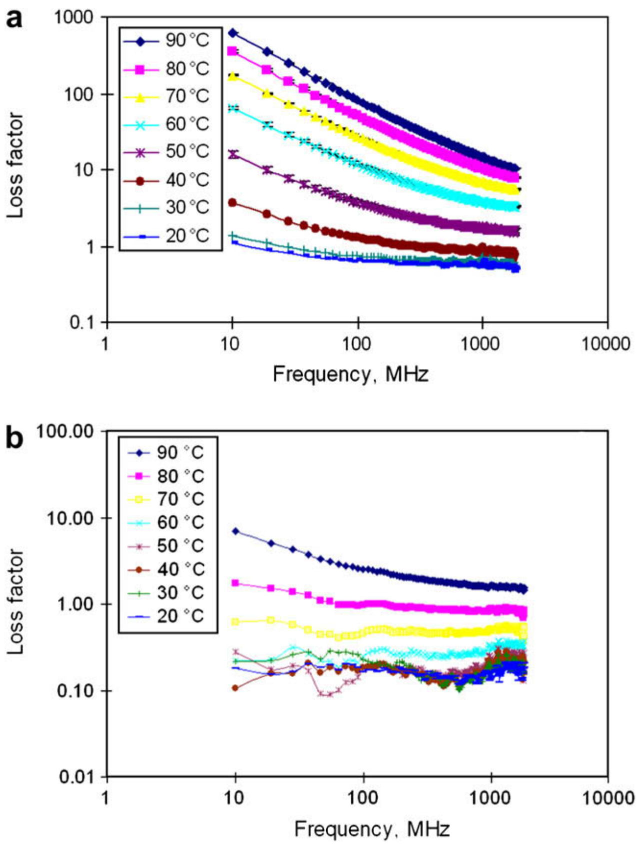

Fig. 2 – The log–log plot of the frequency dependence of the loss factor of 20.9% (a) and 7.9% (b) moisture content chickpea flour sample.

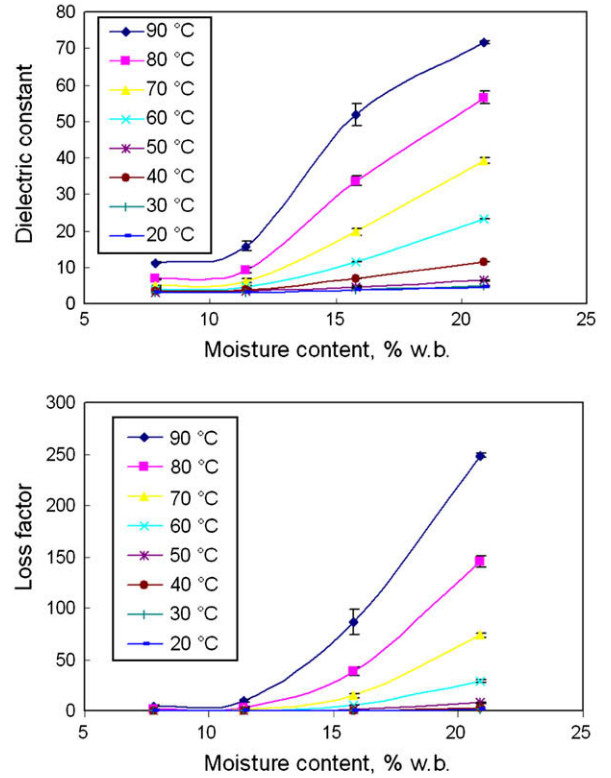

Fig. 3 – Moisture and temperature dependence of the dielectric properties of compressed chickpea flour samples at 27 MHz.

rapid with temperatures above 60 °C, especially at lower frequencies.

When the temperature was raised from 20 to 90 °C, the dielectric constant at 27 MHz increased from 2.99 to 11.20 and the loss factor increased from 0.16 to 4.27 for 7.9% moisture samples, but the dielectric constant increased from 4.50 to 71.59, and the loss factor increased from 0.81 to 248.25 for 20.9% moisture samples.

Temperature dependence of dielectric properties has also been reported in soft red winter wheat (Lawrence *et al.*, 1990) and pecan (Lawrence *et al.*, 1992). The loss factor at RF (27 MHz) in most bio-materials increases with increasing temperature due to increased ionic conductivity as a result of reduced viscosity at high temperatures (Tang *et al.*, 2002). These reports reaffirm that the magnitude of ε' and ε'' is heavily dependent on the product moisture content and temperature. The observed trends in this study can be again

Table 4 – Dielectric properties (mean ± SD) of chickpea flour with 11.4% moisture content at different temperatures over the frequency range from 10 to 1800 MHz

Frequencies, MHz		20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C	90 °C
27	ε'	2.96 ± 0.04	3.03 ± 0.07	3.22 ± 0.08	3.60 ± 0.11	4.37 ± 0.30	6.00 ± 0.67	9.01 ± 0.90	15.35 ± 1.65
	ε''	0.18 ± 0.01	0.15 ± 0.06	0.13 ± 0.12	0.20 ± 0.13	0.40 ± 0.20	1.06 ± 0.42	3.06 ± 0.72	9.41 ± 1.84
40	ε'	2.86 ± 0.06	2.98 ± 0.07	3.12 ± 0.12	3.47 ± 0.17	4.23 ± 0.33	5.79 ± 0.61	8.52 ± 0.78	14.01 ± 1.44
	ε''	0.17 ± 0.01	0.13 ± 0.09	0.14 ± 0.17	0.19 ± 0.20	0.40 ± 0.25	0.97 ± 0.40	2.60 ± 0.66	7.64 ± 1.52
100	ε'	2.86 ± 0.04	2.93 ± 0.03	3.06 ± 0.07	3.39 ± 0.08	4.07 ± 0.21	5.41 ± 0.43	7.58 ± 0.59	11.71 ± 1.01
	ε''	0.19 ± 0.01	0.20 ± 0.05	0.21 ± 0.10	0.28 ± 0.09	0.46 ± 0.12	0.75 ± 0.24	1.26 ± 0.39	2.29 ± 0.87
915	ε'	2.51 ± 0.04	2.58 ± 0.01	2.70 ± 0.03	2.95 ± 0.03	3.45 ± 0.13	4.35 ± 0.29	5.81 ± 0.38	8.36 ± 0.57
	ε''	0.21 ± 0.02	0.23 ± 0.00	0.25 ± 0.03	0.33 ± 0.02	0.46 ± 0.04	0.75 ± 0.09	1.26 ± 0.12	2.29 ± 0.22
1800	ε'	2.43 ± 0.04	2.50 ± 0.01	2.61 ± 0.04	2.83 ± 0.04	3.29 ± 0.15	4.07 ± 0.27	5.37 ± 0.35	7.63 ± 0.53
	ε''	0.21 ± 0.03	0.22 ± 0.04	0.29 ± 0.09	0.39 ± 0.14	0.55 ± 0.18	0.76 ± 0.15	1.30 ± 0.21	2.18 ± 0.26

Table 5 – Dielectric properties (mean ± SD) of chickpea flour with 15.8% moisture content at different temperatures over the frequency range from 10 to 1800 MHz

Frequencies, MHz		20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C	90 °C
27	ε'	3.75 ± 0.13	3.94 ± 0.15	4.70 ± 0.01	6.98 ± 0.06	11.47 ± 0.03	19.76 ± 0.96	33.55 ± 1.35	51.92 ± 3.02
	ε''	0.35 ± 0.02	0.39 ± 0.03	0.62 ± 0.01	1.71 ± 0.02	5.08 ± 0.18	14.75 ± 1.95	38.66 ± 4.26	86.42 ± 12.32
40	ε'	3.68 ± 0.12	3.86 ± 0.15	4.57 ± 0.02	6.67 ± 0.07	10.73 ± 0.05	17.99 ± 0.73	29.71 ± 0.93	44.51 ± 2.01
	ε''	0.36 ± 0.02	0.40 ± 0.04	0.61 ± 0.01	1.54 ± 0.01	4.31 ± 0.12	11.96 ± 1.32	30.29 ± 2.83	65.99 ± 7.96
100	ε'	3.47 ± 0.11	3.64 ± 0.14	4.24 ± 0.02	6.00 ± 0.07	9.21 ± 0.07	14.60 ± 0.50	22.75 ± 0.55	32.27 ± 1.17
	ε''	0.37 ± 0.03	0.41 ± 0.03	0.58 ± 0.01	1.23 ± 0.01	2.93 ± 0.07	7.15 ± 0.77	16.43 ± 1.53	33.07 ± 4.07
915	ε'	2.95 ± 0.07	3.08 ± 0.08	3.54 ± 0.03	4.76 ± 0.08	6.81 ± 0.08	10.05 ± 0.22	14.62 ± 0.22	19.64 ± 0.54
	ε''	0.35 ± 0.03	0.40 ± 0.03	0.54 ± 0.01	0.93 ± 0.02	1.69 ± 0.02	3.10 ± 0.16	5.45 ± 0.25	8.68 ± 0.61
1800	ε'	2.78 ± 0.06	2.89 ± 0.09	3.24 ± 0.04	4.37 ± 0.09	6.18 ± 0.04	9.03 ± 0.23	13.02 ± 0.22	17.50 ± 0.50
	ε''	0.29 ± 0.01	0.34 ± 0.01	0.52 ± 0.02	0.97 ± 0.01	1.69 ± 0.02	2.85 ± 0.17	4.60 ± 0.15	6.88 ± 0.35

attributed to the fact that the values of dielectric properties, in particular loss factor, at low frequencies are influenced by ionic conductivity. The ionic conductivity in turn increases with temperature (Wang *et al.*, 2008) and also likely with moisture content in the tested moisture range as discussed in Section 3.2.

Heating efficiency and non-uniformity are important factors in developing postharvest MW and RF treatments for insect pest control (Wang *et al.*, 2001, 2007a,b). The dielectric property results obtained in this study showed that both dielectric constant and loss factor increased with increasing temperature and moisture content, especially in the RF range (Fig. 3). As such, in a non-uniform electromagnetic field, chickpea may experience thermal runaway in RF treatments in which a rise in product temperature leads to higher dielectric loss factor which in turn increases local RF heating rate, further increasing temperature differences in the same products. It is, therefore, important to develop RF applicators with best possible field uniformity to reduce non-uniform RF heating. As moisture content also influences dielectric properties (Fig. 3), it is also desirable that the treated samples have a narrow range of moisture content.

3.4. *Relationship between permittivity and sample density*

High linear correlations between measured ε' and ε'' divided by bulk densities, ρ, respectively, of grain and seed in complex-plane plots of various moisture contents and temperatures at MW frequencies were first reported by Trabelsi *et al.* (1997). Linear correlation was obtained between ε' and ε'' for a single bulk density in all observed moisture contents of ground wheat samples at temperatures ranging from 5 to 95 °C and frequencies higher than 1.1 GHz, especially at 1.8 GHz (Nelson and Trabelsi, 2006). When the measured dielectric constant and loss factor of compressed chickpea samples at all observed moisture contents and temperatures at a fixed frequency were divided by the sample density, we also obtained a linear correlation between ε'/ρ and ε''/ρ at higher frequencies. Furthermore, the higher the frequency, the better the linear coefficient of determination. For example, the R^2 was 0.984 at 1.2 GHz, while it was 0.995 at 1.8 GHz. The permittivity data, measured at 1.8 GHz for compressed chickpea flour samples, divided by their actual density, listed in Table 2, are shown in Fig. 4 at 7.9%, 11.4%, 15.8% and 20.9%

Table 6 – Dielectric properties (mean ± SD) of chickpea flour with 20.9% moisture content at different temperatures over the frequency range from 10 to 1800 MHz

Frequencies, MHz		20 °C	30 °C	40 °C	50 °C	60 °C	70 °C	80 °C	90 °C
27	ε'	4.50 ± 0.13	4.79 ± 0.09	6.35 ± 0.02	11.43 ± 0.49	23.26 ± 0.09	39.19 ± 0.67	56.51 ± 1.69	71.59 ± 0.30
	ε''	0.81 ± 0.04	0.99 ± 0.04	2.14 ± 0.04	7.85 ± 0.72	28.66 ± 1.41	73.33 ± 1.63	145.88 ± 5.47	248.25 ± 2.09
40	ε'	4.37 ± 0.10	4.63 ± 0.07	6.05 ± 0.02	10.57 ± 0.41	20.85 ± 0.07	34.32 ± 0.54	48.20 ± 1.19	60.14 ± 0.22
	ε''	0.73 ± 0.03	0.88 ± 0.03	1.82 ± 0.03	6.31 ± 0.50	22.17 ± 0.85	55.35 ± 0.84	108.40 ± 3.63	182.28 ± 1.30
100	ε'	4.03 ± 0.08	4.27 ± 0.07	5.41 ± 0.01	8.89 ± 0.29	16.43 ± 0.04	25.86 ± 0.36	34.90 ± 0.75	42.73 ± 0.20
	ε''	0.66 ± 0.03	0.76 ± 0.03	1.31 ± 0.01	3.75 ± 0.29	11.72 ± 0.39	27.07 ± 0.27	50.27 ± 1.87	81.19 ± 0.52
915	ε'	3.33 ± 0.05	3.52 ± 0.03	4.35 ± 0.02	6.64 ± 0.20	11.19 ± 0.08	16.62 ± 0.06	21.67 ± 0.24	26.43 ± 0.24
	ε''	0.54 ± 0.03	0.60 ± 0.01	0.84 ± 0.01	1.71 ± 0.09	3.84 ± 0.04	6.98 ± 0.04	10.69 ± 0.26	14.96 ± 0.04
1800	ε'	3.12 ± 0.01	3.22 ± 0.01	4.03 ± 0.05	6.14 ± 0.15	10.25 ± 0.03	15.06 ± 0.08	19.50 ± 0.18	23.80 ± 0.21
	ε''	0.52 ± 0.01	0.55 ± 0.03	0.80 ± 0.03	1.61 ± 0.11	3.34 ± 0.04	5.60 ± 0.06	7.87 ± 0.17	10.39 ± 0.01

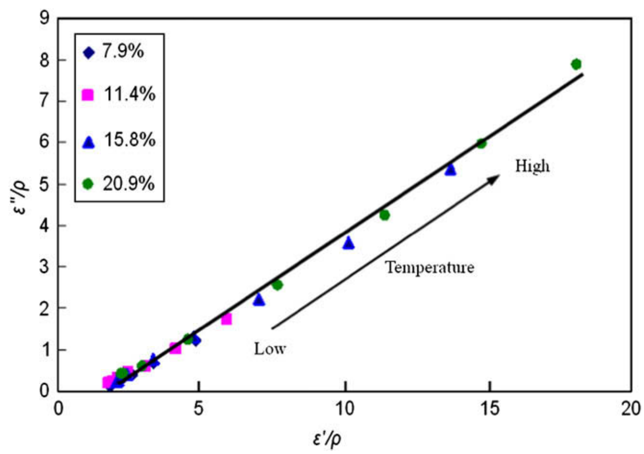

Fig. 4 – Complex-plane plot of chickpea flour samples of four moisture contents at 20–90 °C and 1.8 GHz, $R^2 = 0.995$.

moisture contents at various temperatures. All data are clearly distributed along a straight regression line:

$$\frac{\varepsilon''}{\rho} = 0.4552\frac{\varepsilon'}{\rho} - 0.8046 \quad (2)$$

with $R^2 = 0.995$ and

$$\rho = 0.5657\varepsilon' - 1.2429\varepsilon'' \quad (3)$$

Eq. (2) suggests that the dielectric properties of chickpea flour can be estimated from its density at 1.8 GHz. It can also be useful to estimate the chickpea flour sample's density, if dielectric properties are known (Eq. (3)).

4. Conclusions

Dielectric properties of chickpea flour samples as a function of frequency, moisture and temperature were measured with an open-ended coaxial-line probe, impedance analyzer, and suitable sample temperature control equipment. Both dielectric constant and loss factor of chickpea samples decreased with increases in frequency over the detected frequency range from 10 to 1800 MHz. Negative linear relationship was found in the log–log plot of frequency and loss factor at lower frequencies. At those frequencies, ionic conduction was the predominant factor that influences dielectric loss for chickpea samples. The dielectric constant and loss factor increased with increasing moisture content from 7.9% to 20.9% and also increased with increases in temperature in the range from 20 to 90 °C. Higher moisture contents and temperatures had greater influence on permittivity than lower moisture contents and temperatures. These results may be useful in dielectric heating applications, and in developing potential new dielectric property based moisture meters.

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