SENSING MOISTURE CONTENT OF BUCKWHEAT SEED FROM DIELECTRIC PROPERTIES

X. Zhu, W. Guo, S. Wang

ABSTRACT. *Dielectric properties (dielectric constant and dielectric loss factor) of static buckwheat seed were determined in the ranges of 1 to 1000 kHz for frequency of the electric field, 11.1% to 17.1% wet basis for moisture content, 722.1 to 800.6 kg m^{-3} for bulk density, and 5°C to 40°C for temperature using a coaxial cylindrical capacitor. The influences of frequency, moisture content, bulk density, and temperature on the dielectric properties were investigated. Polynomials were developed describing the relationships between permittivities and moisture content, temperature, and bulk density at selected frequencies. The significance of each factor on the regression models was analyzed, and the accuracy of the models for calculating permittivites and for sensing moisture content was evaluated. The results showed that dielectric constant and loss factor both decreased with increasing frequency and increased with increasing moisture content, bulk density, and temperature. The second-order and third-order polynomials could be used to describe the relationships between permittivities and affecting factors at selected frequencies. Moisture content and temperature were significant factors influencing the dielectric properties of buckwheat. The regression models were verified to be accurate for calculating the dielectric constant and loss factor and for sensing moisture content from the obtained dielectric properties. This study offers useful information on dielectric properties of buckwheat and suggests that dielectric measurement can be used in sensing moisture content of buckwheat.*

Keywords. *Buckwheat, Bulk density, Dielectric properties, Frequency, Moisture content, Temperature.*

Buckwheat (*Fagopyrum*) is an alterative but underutilized crop that belongs to the *Polygonaceae* family (Zhou et al., 2009). Common buckwheat (*Fagopyrum esculentum* Moench) and tartary buckwheat (*Fagopyrum tataricum* Moench) are two main varieties consumed around the world (Krkošková and Mrázová, 2005). Russia is now the largest producer of buckwheat, and China is in the second position (Krkošková and Mrázová, 2005). The increased interest in studying buckwheat in recent years is due not only to buckwheat's abundance in nutrition, such as protein, essential amino acids, dietary fiber, starch, vitamins B1, B2, C, and E, and trace elements (Ikeda and Yamashita, 1994; Nikolić et al., 2011; Watanabe, 1998), but also to its well balanced amino acid composition and effectiveness in controlling blood vessels for preventing edema, hemorrhagic diseases, and stabilizing high blood pressure (Nikolić et al., 2011; Tang et al., 2009). Therefore, the cultivated area and the yield of buckwheat in China have been increasing continuously in recent years.

Appropriate moisture content of buckwheat can reduce loss in harvesting. High moisture content results in spoilage during storage. Moisture content is a dominant factor that influences shelf life, although temperature, relative humidity, and degree of fungal infection and insect infestation also influence shelf life (Berbert et al., 2002; Lawrence and Nelson, 1993). Since the unit price of buckwheat is based on weight, of which a portion is water, moisture content is usually listed as a primary criterion in the consumer market. Moisture measurement and control are also important in many postharvest processes, such as milling, because appropriate moisture content ensures flour quality. Therefore, moisture content is the most important factor during buckwheat harvesting, drying, storing, marketing, and processing.

Oven drying is a standard and popular method for buckwheat moisture determination, but the long drying time required is its major disadvantage. Furthermore, oven drying cannot be applied in on-line moisture determination. The literature has shown that the dielectric properties of grains and seeds have high correlations with their moisture contents. In addition to moisture content, the frequency of the applied electric field, temperature, and bulk density of grains and seeds have also been identified as important variables of dielectric properties (Guo et al., 2012; Guo et al., 2010; Lawrence and Nelson, 1993; Nelson, 1982; Sacilik and Colak, 2010; Trabelsi and Nelson, 2004, 2006).

Knowledge of the relationships between the dielectric properties and moisture content, temperature, and bulk density of buckwheat and the frequency of the electric field is helpful to develop a portable, time-saving, precise, and on-line electronic instrument for rapidly determining the

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moisture content of buckwheat. However, to our knowledge, no investigation has been conducted on the dielectric properties of buckwheat as a function of moisture content, temperature, bulk density, and frequency. Therefore, the objectives of this study were: (1) to obtain the dielectric properties of static samples of buckwheat seed in the ranges of 11.1% to 17.1% wet basis (w.b.) for moisture content, 722.1 to 800.6 kg m^{-3} for bulk density, 5°C to 40°C for temperature, and 1 to 1000 kHz for frequency of the electric field using a coaxial cylindrical capacitor; (2) to develop mathematical models describing the relationships between permittivities and moisture content, temperature, and bulk density at certain frequencies; and (3) to evaluate the accuracy of the developed mathematical models in calculating dielectric properties and in sensing moisture content.

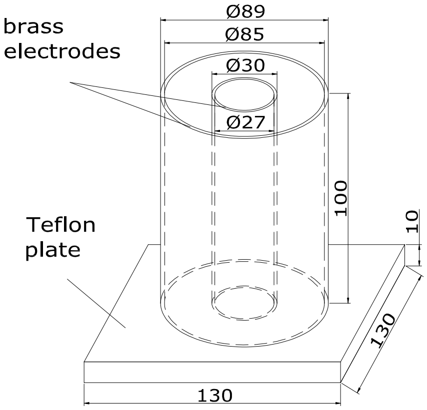


Figure 1. Diagram of the coaxial cylindrical capacitor.

MATERIALS AND METHODS

SAMPLES AND SAMPLE PREPARATION

The common buckwheat without chaff used in this study was purchased from a local supermarket in Yangling, China. It was cleaned manually to remove all foreign matter, such as dirt, dust, and stone, as well as broken and immature seeds. Samples at initial moisture content of 11.1% w.b. were placed in polyethylene bags, and calculated amounts of distilled water were added by spraying a fine mist into each bag to raise the moisture content to the desired level. The bags were sealed and shaken to aid the distribution of moisture. The samples in bags were then stored in a refrigerator at 4°C for at least four days. For moisture contents higher than 15.0%, the water was added in two or three steps with an interval of three days. During storage, the bags were shaken four to six times per day to achieve uniform moisture distribution. Before measurements, the samples were taken from the refrigerator and allowed to equilibrate to room temperature for at least 12 h. The moisture contents of the samples were then determined by drying triplicate samples of about 10 g in aluminum dishes for 18 h at a temperature of 103°C in a forced-air oven (WG-71, Tianjin Taisite Instrument Co., Ltd., Tianjin, China) (*ASAE Standards*, 2005). All moisture contents were calculated on a wet basis. Buckwheat samples at moisture contents of 11.1% (initial moisture content), 13.1%, 15.1%, and 17.1% w.b. were obtained in this study. At each moisture level, the samples were divided into three sublots, which were used independently to determine dielectric properties at three different bulk densities.

DETERMINATION OF DIELECTRIC PROPERTIES

The dielectric properties of interest in most applications are the dielectric constant (ε') and the dielectric loss factor (ε''), the real part and imaginary part, respectively, of the relative complex permittivity (ε^*): $\varepsilon^* = \varepsilon' - j\varepsilon''$, where $j = \sqrt{-1}$. 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. The dielectric constant of a material is commonly considered to be the ratio of the capacitance of a capacitor, with the material as its dielectric, to the capacitance of the same capacitor with air, or more properly vacuum, as the dielectric (Berbert et al., 2001; Nelson and Stetson, 1976). That is:

$$\varepsilon' = \frac{C}{C_0} \tag{1}$$

where C and C_0 are the capacitances of the sample-filled capacitor and the empty capacitor (pF), respectively.

The dielectric loss factor can be calculated as (Lawrence and Nelson, 1993):

$$\varepsilon'' = \frac{G - G_0}{2\pi f C_0} \tag{2}$$

where G and G_0 are conductance values (S) of the sample-filled and empty capacitor, respectively, and f is the frequency of the electric field (Hz).

An LCR meter (3532-50, Hioki E.E. Corp., Nagano, Japan) was used to measure the values of capacitance and conductance of buckwheat samples at 51 discrete frequencies on a logarithmic scale from 1 to 1000 kHz. The LCR meter was connected to a fabricated coaxial cylindrical capacitor. The capacitor was made of two coaxial cylindrical brass electrodes of 100 mm height. The internal diameter of the outer electrode was 85 mm. The inner electrode had an external diameter of 30 mm. A Teflon plate held the electrodes in place at the bottom of the test cell. A diagram of the coaxial cylindrical capacitor is shown in figure 1.

EXPERIMENTAL PROCEDURES

Before measuring the dielectric properties, the LCR meter was turned on and allowed to warm up for about 1 h. After the mass of the empty coaxial cylindrical capacitor (air filled) was determined, the capacitor was placed in a far-infrared constant-temperature oven (YHG-400BS, Shanghai Yuejin Medical Instruments Factory, Shanghai, China). The temperature of the oven was set from 5°C to 40°C at 5°C intervals. Capacitance and conductance values were measured at 51 discrete frequencies from 1 to 1000 kHz on the empty capacitor, which was covered with a Teflon plate, at each temperature, and these values were used as C_0 and G_0 in equations 1 and 2, respectively, at the

Table 1. Bulk density of buckwheat samples at four moisture contents.

Bulk Density Level	Bulk Density (kg m^{-3})			
	11.1% w.b.	13.1% w.b.	15.1% w.b.	17.1% w.b.
Loose fill	754.7	745.6	731.5	720.5
Middle fill	776.2	764.3	752.1	738.0
Dense fill	800.6	786.7	773.8	759.1

corresponding temperatures. Since the bulk density of the buckwheat samples was not easily changed, only three bulk densities (denoted loose fill, middle fill, and dense fill) were used at each moisture level. Loose fill was achieved by filling the capacitor with buckwheat as loosely as possible. Middle fill was obtained by mildly pressing the buckwheat into the capacitor. Dense fill was achieved by repeatedly shaking the capacitor filled with buckwheat and pressing the buckwheat on the top. The capacitor filled with buckwheat was weighed, and the bulk density was determined by dividing the mass of the sample by the volume of the material. The bulk densities obtained at four moisture contents are listed in table 1.

The capacitor filled with buckwheat at a given moisture content and bulk density was covered with a Teflon plate and placed in a refrigerator at -18°C for about 6 h to obtain a sample whose temperature was lower than 5°C. The capacitor was then taken from the refrigerator and placed in the YHG-400BS constant-temperature oven. The capacitor was covered with a Teflon plate with a 5 mm hole in the center to avoid moisture loss. A type-T thermocouple was inserted through this hole into the middle of the capacitor to about 50 mm depth. Previous experiments showed that the influence of the thermocouple on the capacitance and conductance values of buckwheat was very small. Therefore, its effect was neglected in this study. The oven temperature was set at 5°C, 10°C, 15°C, 20°C, 25°C, 30°C, 35°C, and 40°C in sequence. After the sample temperature reached a set level and remained constant, the capacitance and conductance were measured three times at 51 discrete frequencies from 1 to 1000 kHz. Duplicates were performed for each bulk density. The dielectric constant and loss factor were calculated using equations 1 and 2, respectively, and the averages at each combination of moisture content, bulk density, and temperature were used in the results. To determine moisture loss during the measurement, the mass of the capacitor filled with buckwheat was weighed after each measurement, which showed that the moisture losses were less than 0.3%. During the experiment, the room temperature was controlled at 24°C ±2°C.

MODELING AND MODEL VALIDATION

The data obtained in this study were analyzed using Design-Expert 7.1.6 (Stat Ease, Minneapolis, Minn.) to regress the mathematical models describing the relationships between permittivities (dielectric constant and loss factor) and moisture content, temperature, and bulk density of buckwheat at selected frequencies. Buckwheat samples at eight moisture levels from 11.1% to 17.1% w.b were randomly prepared. Their permittivity values were measured at randomly selected temperatures between 5°C and 40°C and at bulk densities in the range of 722 to 800 kg m^{-3}. In all, 48 measurements were done. Linear regressions between the dielectric properties measured with the coaxial cylindrical capacitor and calculated using the regressed mathematical models were applied to evaluate the accuracy of the regression models.

VERIFICATION OF FEASIBILITY OF SENSING MOISTURE CONTENT FROM DIELECTRIC PROPERTIES

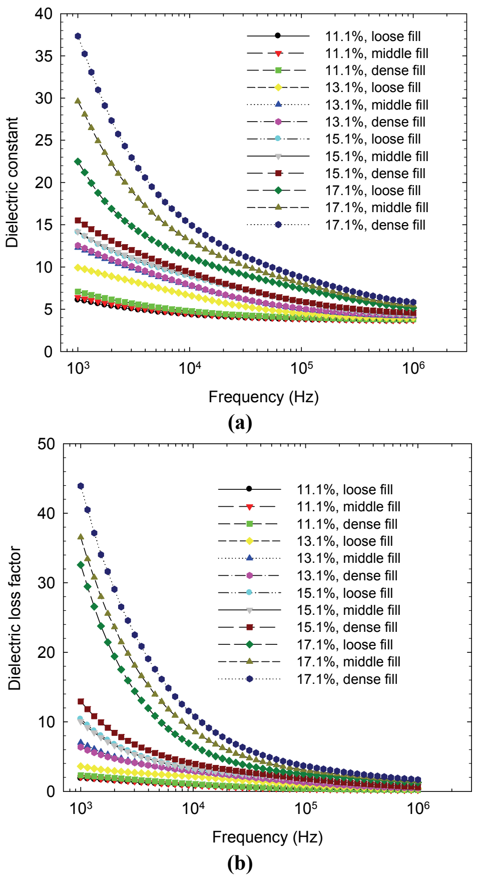
Another batch of buckwheat samples at moisture contents from 11.1% to 17.1% w.b. was prepared. The dielectric properties of buckwheat were obtained with the coaxial capacitor at randomly obtained bulk densities from 722 to 800 kg m^{-3} and at random temperatures from 5°C to 40°C. The Newton iteration method was used to calculate moisture content using the obtained dielectric properties, known temperature, and bulk density from regressed mathematical models describing the relationships between dielectric properties and moisture content, temperature, and bulk density. The moisture contents measured with the oven-drying method and the calculated values were compared to assess the feasibility of sensing moisture content of buckwheat from dielectric properties.

RESULTS AND DISCUSSION

INFLUENCE OF FREQUENCY, MOISTURE CONTENT, TEMPERATURE, AND BULK DENSITY ON DIELECTRIC PROPERTIES

The frequency-dependent dielectric constant (fig. 2a) and loss factor (fig. 2b) of loose, middle, and dense fill buckwheat samples at four moisture contents and 25°C are shown in figure 2. The results illustrate that the values of ε' and ε'' decreased with increasing frequency from 1 to 1000 kHz at each given moisture content and a given bulk density. The decrease was greater at lower frequencies than at higher frequencies, especially at higher moisture contents. Similar frequency-dependent dielectric properties were observed at other temperatures. The moisture content and bulk density did not affect the decreasing trend of ε' and ε'' with increasing frequency. However, at a given frequency, the values of ε' and ε'' were larger at higher moisture contents than at lower levels.

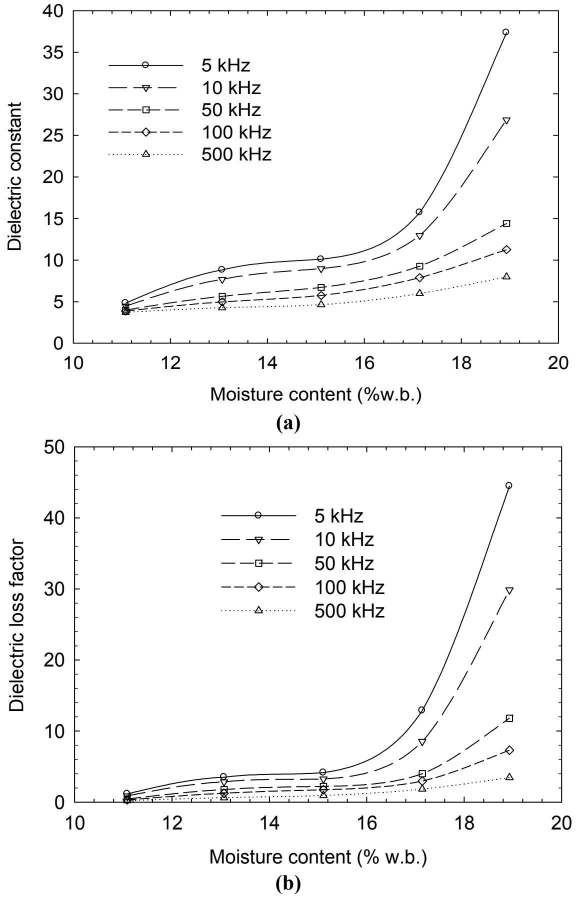
The effects of moisture content on ε' and ε'' of middle fill buckwheat samples at 25°C and the indicated frequencies are shown in figure 3. Depending on the frequency, both ε' and ε'' increased with an increase in moisture content. When the moisture content was below 15.1%, the values of ε' and ε'' increased a little, but the increase was greater above 15.1%. Since the dielectric constant of free water at room temperature is about 80, while that of grain dry matter is less than 3 in the lower radio-frequency range (Lawrence et al., 1998), higher moisture content means a higher dielectric constant. Similar results were found in many previous studies on grains (Lawrence and Nelson, 1993; Nelson and Stetson, 1976; Sacilik and Colak, 2010), cereals (Berbert et al., 2002; Guo et al., 2008; Guo et al., 2010; Guo et al., 2012; Jiao et al., 2011), and nuts (Nelson, 1981; Trabelsi and Nelson, 2004), and wheat straw (Guo et al., 2013).



(a)

(b)

Figure 2. Frequency-dependent (a) dielectric constant and (b) loss factor of loose, middle, and dense fill buckwheat samples over the frequency range of 1 to 1000 kHz at 25°C and the indicated moisture contents.



(a)

(b)

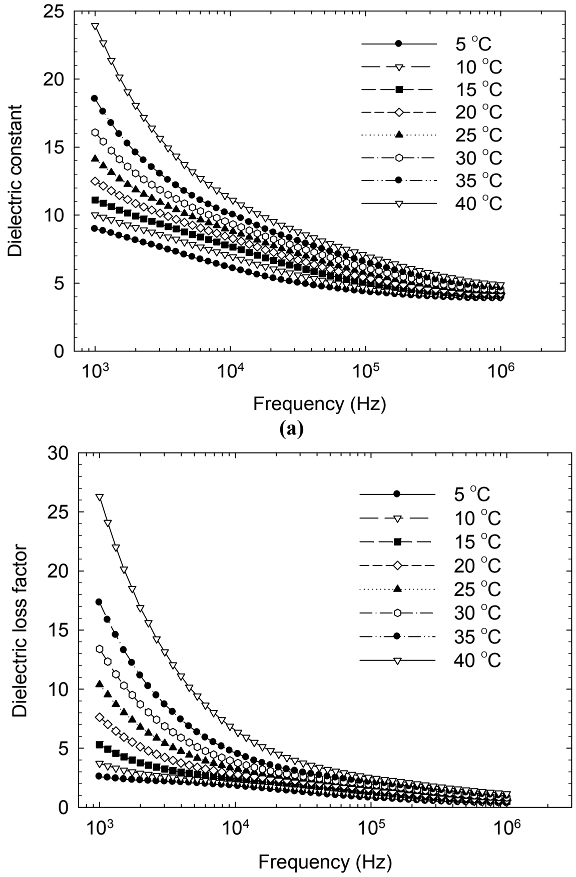
Figure 3. Moisture-dependent (a) dielectric constant and (b) loss factor of middle fill buckwheat samples at 25°C and the indicated frequencies.

The frequency- and temperature-dependent ε′ and ε″ of loose fill buckwheat samples at moisture content of 15.1% w.b. and temperatures from 5°C to 40°C over the frequency range of 1 to 1000 kHz are shown in figure 4. Temperature had negligible effect on the decreasing trend of ε′ and ε″ with an increase in frequency. Similar frequency- and temperature-dependent dielectric properties were observed for buckwheat samples at other moisture contents and bulk densities. At a given frequency, buckwheat samples at higher temperatures had larger values of ε′ and ε″ than at lower temperatures, especially at lower frequencies.

The influence of temperature on ε′ and ε″ of loose fill buckwheat seed samples at 100 kHz and the four investigated moisture levels is presented in figure 5. The data show that ε′ and ε″ both increased with increasing temperature. At any given temperature, the values of ε′ and ε″ were larger at higher moisture contents than at lower levels. Increasing ε′ and ε″ values with increasing temperature have been reported for corn (Nelson, 1979), wheat (Lawrence et al., 1990; Nelson and Trabelsi, 2006), pecans (Lawrence et al., 1992), legumes (Guo et al., 2008; Guo et al., 2010; Guo et al., 2012; Jiao et al., 2011), and chestnuts (Guo et al., 2011).

In addition to frequency, moisture content, and temperature, the permittivity values of buckwheat were also influenced by bulk density. Figure 6 shows the effect of bulk density on ε′ and ε″ at 10 kHz, 25°C, and the four moisture contents. At any given moisture content, ε′ and ε″ increased with an increase in bulk density. Above 15.1%, the effect of bulk density on permittivities was more obvious. Except for 13.1% w.b., ε′ and ε″ increased almost linearly with bulk density. The nonlinear effect at 13.1% may have been caused by measurement error from the sample, instrument, measuring method, etc. Similar trends were obtained at other temperatures and frequencies. Denser packing caused a reduction in porosity and increase in the buckwheat sample in a given volume (Sacilik et al., 2007). Therefore, higher bulk density means higher ε′ and ε″. This conclusion is in agreement with the results for wheat and corn (Kraszewski et al., 1996; Lawrence et al., 1998; Nelson, 1979; Sacilik and Colak, 2010; Sokhansanj and Nelson, 1988; Trabelsi and Nelson, 2003), peanuts (Boldor et al., 2004; Trabelsi and Nelson, 2004), safflower seeds (Sacilik et al., 2007), flaxseed (Sacilik et al., 2006), and soybeans (Trabelsi and Nelson, 2003).

This study reaffirms that the values of ε′ and ε″ are dependent on the frequency of the electric field and the moisture content, temperature, and bulk density of grains and seeds.



(a)

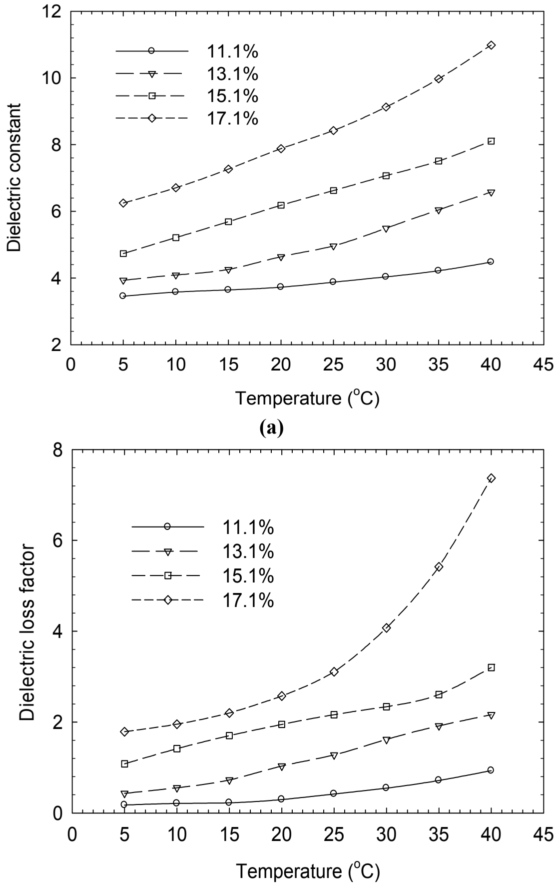
(b)

Figure 4. Frequency- and temperature-dependent (a) dielectric constant and (b) loss factor of loose fill buckwheat samples over the frequency range of 1 to 1000 kHz at 15.1% w.b. moisture content and the indicated temperatures.

MATHEMATICAL MODELS FOR DIELECTRIC PROPERTIES

Third-order polynomial models can be used to describe the relationships between the permittivities (ε′ and ε″) and moisture content, temperature, and bulk density at 10, 50, 100, 500 and 1000 kHz. Each model provided a good fit to the experimental data with a value of R^2 (coefficient of determination) greater than 0.985. When ε′ and ε″ were dependent variables, the models at 500 kHz had the highest R^2, followed by 1000 kHz and 100 kHz. The models at 100 kHz and 500 kHz are as follows:

$$\begin{aligned}\varepsilon'_{100\mathrm{kHz}} = {} & 1.40\times10^{5} - 3023W + 3.31T - 4.98\rho \\ & -0.0832WT + 7.26W\rho - 7.32\times10^{-3}T\rho \\ & +19.3W^{2} - 4.82\times10^{-3}T^{2} + 0.59\rho^{2} \\ & +1.10\times10^{-4}WT\rho + 5.12\times10^{-4}W^{2}T \\ & -0.025W^{2}\rho + 4.83\times10^{-5}WT^{2} \\ & -4.32\times10^{-3}W\rho^{2} + 4.86\times10^{-6}T^{2}\rho \\ & +3.83\times10^{-6}T\rho^{2} - 7.64\times10^{-3}W^{3} \\ & +1.61\times10^{-5}T^{3} - 2.32\times10^{-4}\rho^{3} \\ & \left(\mathrm{R}^{2} = 0.998\right)\end{aligned} \tag{3}$$



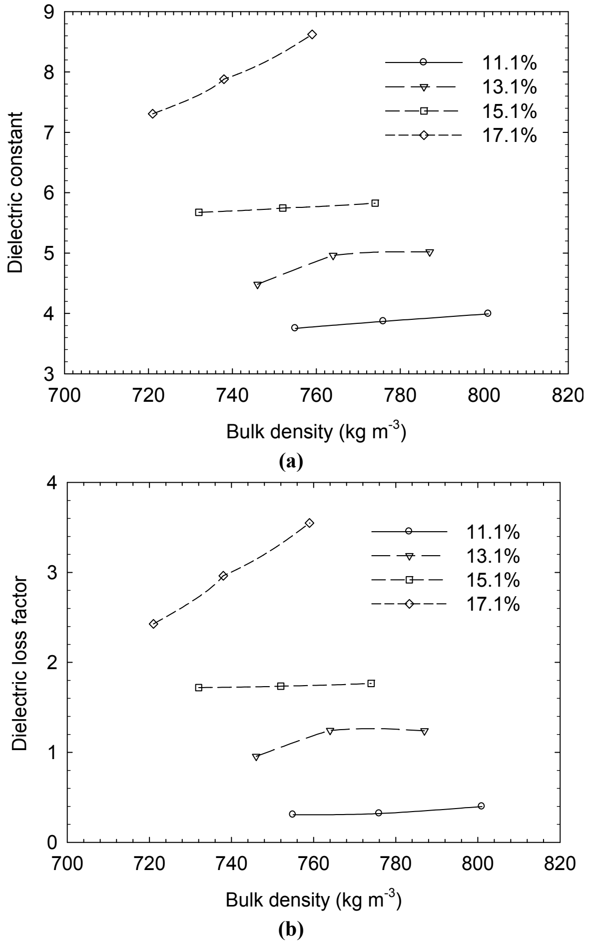
(a)

(b)

Figure 5. Temperature-dependent (a) dielectric constant and (b) loss factor of loose fill buckwheat samples at 100 kHz and the indicated moisture contents.

$$\begin{aligned}\varepsilon''_{100\mathrm{kHz}} = {} & 1.18\times10^{5} - 2563W + 5.72T - 419\rho \\ & -0.260WT + 6.10W\rho - 0.0103T\rho \\ & +16.03W^{2} - 0.0129T^{2} + 0.496\rho^{2} \\ & +2.24\times10^{-4}WT\rho + 3.12\times10^{-3}W^{2}T \\ & +0.0209W^{2}\rho + 4.42\times10^{-4}WT^{2} \\ & -3.64\times10^{-3}W\rho^{2} + 7.49\times10^{-6}T^{2}\rho \\ & -4.78\times10^{-6}T\rho^{2} - 5.76\times10^{-3}W^{3} \\ & +3.11\times10^{-5}T^{3} - 1.95\times10^{-4}\rho^{3} \\ & \left(\mathrm{R}^{2} = 0.987\right)\end{aligned} \tag{4}$$

$$\begin{aligned}\varepsilon'_{500\mathrm{kHz}} = {} & 63068 - 1349W + 1.24T - 224\rho \\ & -0.0525WT + 3.25W\rho - 2.50\times10^{-3}T\rho \\ & +8.34W^{2} + 4.51\times10^{-5}T^{2} + 0.266\rho^{2} \\ & +3.24\times10^{-5}WT\rho + 1.24\times10^{-3}W^{2}T \\ & -0.011W^{2}\rho + 4.97\times10^{-5}WT^{2} \\ & -1.94\times10^{-3}W\rho^{2} - 1.10\times10^{-6}T^{2}\rho \\ & +1.43\times10^{-6}T\rho^{2} + 2.61\times10^{-3}W^{3} \\ & +6.06\times10^{-6}T^{3} - 1.05\times10^{-4}\rho^{3} \\ & \left(\mathrm{R}^{2} = 0.998\right)\end{aligned} \tag{5}$$



(a)

(b)

Figure 6. Bulk density-dependent (a) dielectric constant and (b) loss factor of buckwheat samples at 10 kHz, 25°C, and the indicated moisture contents.

$$
\begin{aligned}
\varepsilon''_{500\mathrm{kHz}} = {} & 59879 - 1292W + 1.70T - 213\rho \\
& -0.0597WT + 3.10W\rho - 3.42\times10^{-3}T\rho \\
& +8.24W^2 - 3.83\times10^{-3}T^2 + 0.252\rho^2 \\
& +6.31\times10^{-5}WT\rho + 6.15\times10^{-4}W^2T \\
& -0.111W^2\rho + 6.74\times10^{-5}WT^2 \\
& -1.85\times10^{-3}W\rho^2 + 3.53\times10^{-6}T^2\rho \\
& +1.66\times10^{-6}T\rho^2 - 3.64\times10^{-3}W^3 \\
& +8.85\times10^{-6}T^3 - 9.93\times10^{-5}\rho^3 \\
& \left(\mathrm{R}^2 = 0.998\right)
\end{aligned}
\tag{6}
$$

where $\varepsilon'_{100\mathrm{kHz}}$ and $\varepsilon''_{100\mathrm{kHz}}$ are the ε' and ε'' obtained at 100 kHz, respectively; $\varepsilon'_{500\mathrm{kHz}}$ and $\varepsilon''_{500\mathrm{kHz}}$ are the ε' and ε'' obtained at 500 kHz, respectively; W is the moisture content (% w.b., $11.1 \le W \le 17.1$); T is the temperature (°C, $5 \le T \le 40$); and ρ is the bulk density (kg m^{-3}, $722.1 \le \rho \le 800.6$). The R^2 values of these regression models were very close to each other.

Results of the analysis of variance for equations 3 and 4 (Table 2) showed that except for the third-order terms $WT\rho$, $T^2\rho$, $T\rho^2$, W^3, and T^3, every term in equation 3 was a significant factor at a 0.01 significance level, and the terms $T^2\rho$, $T\rho^2$, W^3, and T^3 were also not significant factors in equation 4. Most terms had a strong influence on these regression models at a 0.0001 significance level. Similar results were also found in other regressed third-order polynomial models at 10, 50, 500, and 1000 kHz.

Table 2. Analysis of variance results for equations 3 and 4.[a]

	Equation 3		Equation 4	
Variance	p > F	Significance	p > F	Significance
W	<0.0001	**	<0.0001	**
T	<0.0001	**	<0.0001	**
ρ	<0.0001	**	<0.0001	**
WT	<0.0001	**	<0.0001	**
$W\rho$	<0.0001	**	<0.0001	**
$T\rho$	0.0040	**	<0.0001	**
W^2	<0.0001	**	0.0074	**
T^2	<0.0001	**	<0.0001	**
ρ^2	<0.0001	**	<0.0001	**
$WT\rho$	0.2742	-	0.0065	**
W^2T	<0.0001	**	<0.0001	**
$W^2\rho$	<0.0001	**	<0.0001	**
WT^2	0.0099	**	0.0011	**
$W\rho^2$	<0.0001	**	<0.0001	**
$T^2\rho$	0.6773	-	0.0843	-
$T\rho^2$	0.5102	-	0.3176	-
W^3	0.3086	-	0.0657	-
T^3	0.2126	-	0.1188	-
ρ^3	<0.0001	**	<0.0001	**
Model	<0.0001	**	<0.0001	**

[a] p is the significance of the probability; asterisks (**) indicate that the term is a significant factor at a significance level of 0.01.

Without regarding the influence of buck density, the second-order polynomial models used to sense ε' and ε'' of buckwheat from moisture content and temperature at 10, 50, 100, 500, and 1000 kHz were regressed. Results showed that each model provided a good fit to the experimental data, with an R^2 value greater than 0.964. The highest R^2 values were found at 100 and 500 kHz for both ε' and ε''. The models are:

$$
\begin{aligned}
\varepsilon'_{100\mathrm{kHz}} = {} & -7.92 + 2.88W - 0.21T + 0.0214WT - 0.246W^2 \\
& +4.01T^2 - 2.60\times10^{-4}W^2T + 1.68\times10^{-6}WT^2 \\
& +7.12\times10^{-3}W^3 + 3.96\times10^{-6}T^3 \\
& \left(\mathrm{R}^2 = 0.986\right)
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
\varepsilon''_{100\mathrm{kHz}} = {} & -16.2 + 3.14W + 0.326T - 0.0378WT \\
& -0.208W^2 - 5.78\times10^{-3}T^2 \\
& +1.21\times10^{-3}W^2T + 3.50\times10^{-4}WT^2 \\
& +4.90\times10^{-3}W^3 + 2.81\times10^{-5}T^3 \\
& \left(\mathrm{R}^2 = 0.983\right)
\end{aligned}
\tag{8}
$$

$$
\begin{aligned}
\varepsilon'_{500\mathrm{kHz}} = {} & -19.3 + 4.92W + 0.122T - 0.021WT \\
& -0.356W^2 - 3.68\times10^{-4}T^2 \\
& +9.49\times10^{-4}W^2T + 6.76\times10^{-5}WT^2 \\
& +8.72\times10^{-3}W^3 - 2.63\times10^{-6}T^3 \\
& \left(\mathrm{R}^2 = 0.986\right)
\end{aligned}
\tag{9}
$$

Table 3. R^2 values of correlations between measured permittivities (dielectric constant and loss factor) and values calculated using equations 3 through 10.

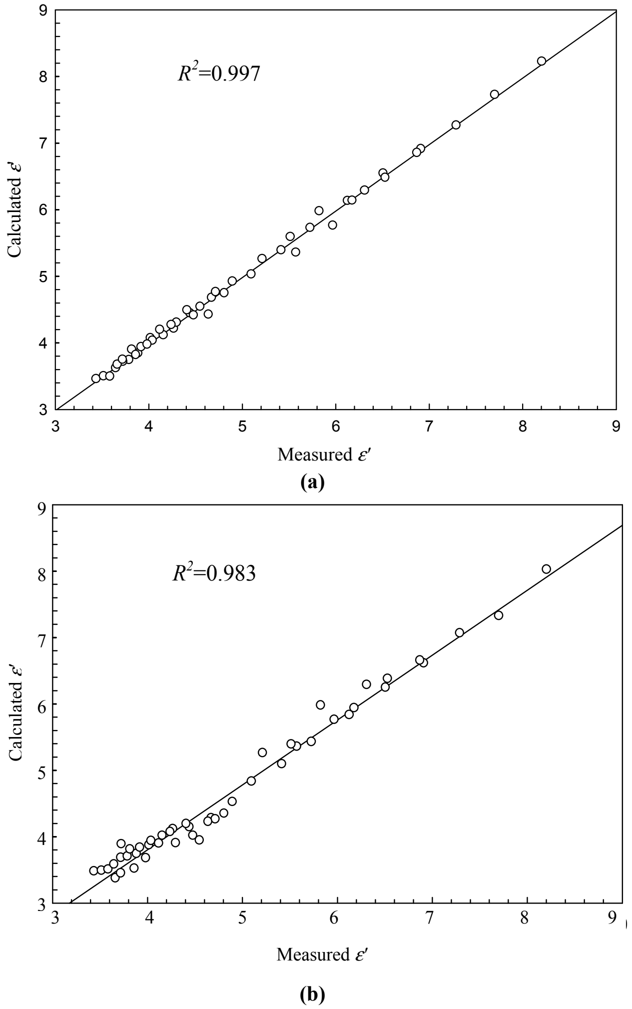
Frequency (kHz)	Permittivity	With Bulk Density Eq.	With Bulk Density R^2	Without Bulk Density Eq.	Without Bulk Density R^2
100	Dielectric constant (ε′)	(3)	0.996	(7)	0.983
	Loss factor (ε″)	(4)	0.985	(8)	0.981
500	Dielectric constant (ε′)	(5)	0.997	(9)	0.983
	Loss factor (ε″)	(6)	0.996	(10)	0.980

$$\begin{aligned}\varepsilon''_{500\text{kHz}} &= -3.22 + 0.874W - 0.027T + 8.76\times10^{-4}WT \\ &\quad -0.076W^2 - 5.47\times10^{-4}T^2 + 1.42\times10^{-4}W^2T \\ &\quad +4.12\times10^{-5}WT^2 + 2.25\times10^{-3}W^3 \\ &\quad +5.23\times10^{-6}T^3 \\ &\quad \left(\mathrm{R}^2 = 0.983\right)\end{aligned} \tag{10}$$

The analysis of variance for equations 7 through 10 showed that each term had significant influence on the models at a 0.01 significance level.

MODEL EVALUATION

The linear R^2 values of measured permittivities (ε′ and ε″) using the coaxial capacitor and the calculated permittivities from equations 3 through 10 using the given moisture content, temperature, and bulk density of randomly prepared buckwheat samples at 100 and 500 kHz are listed in table 3. For given permittivities (dielectric constant and loss factor), the models using bulk density as a variable had higher R^2 values than the models without bulk density. For example, for dielectric constant (ε′), the R^2 of equation 5 was 0.997 (fig. 7a), while R^2 was 0.983 for equation 9 (fig. 7b). The error of calculated versus measured dielectric constant was between -0.14 and 0.23 for equation 5 (fig. 7a) and was within -0.15 to 0.52 for equation 9 (fig. 7b). Therefore, it can be stated that using bulk density as a variable could offer better fit to the experimental data. However, calculation with a third-order polynomial is more complicated than with a second-order polynomial. To improve speed in calculating dielectric properties, only moisture content and temperature can be used.



(a)

(b)

Figure 7. Measured dielectric constant of buckwheat samples versus calculated values from (a) equation 5 and (b) equation 9.

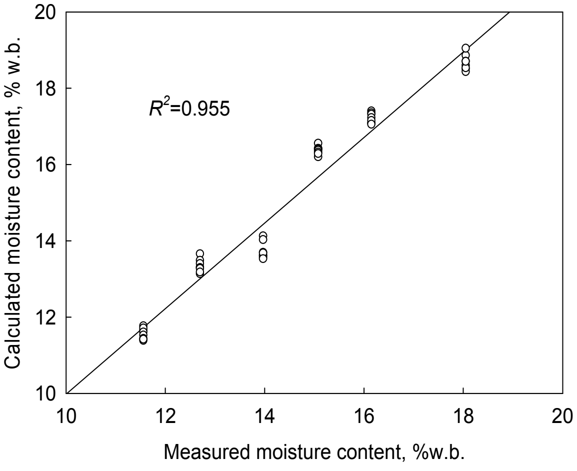


Figure 8. Measured moisture content of buckwheat from the oven-drying method and calculated value from equation 7 using dielectric properties and known temperatures.

SENSING MOISTURE CONTENT FROM DIELECTRIC PROPERTIES

The measured moisture contents versus the calculated values using the obtained dielectric constant and known temperature from equation 7 are shown in figure 8. The R^2 value in figure 8 is 0.955. The error between measured and calculated moisture contents was within -1.2% to 0.4% w.b. When predicting moisture content using equation 8, the R^2 value was 0.948, and the error was within -1.4% to 0.6%. This means that the moisture content of buckwheat could be sensed from dielectric properties. In addition, when bulk density was used to predict moisture content with dielectric properties and temperature, the R^2 value between the measured moisture content and the calculated values from equations 3 through 6 was not higher than the R^2 value for the calculated values from equations 7 through 10. Moreover, when a single-chip microcomputer running at 11.0592 MHz was used in the moisture content calculation, more than 15 s was required when bulk density information was used, in contrast to less than 3 s without bulk density. Therefore, shortening the calculation time is very important for developing a moisture sensor with fast response.

CONCLUSIONS

A coaxial cylindrical capacitor was used to measure the dielectric properties of static buckwheat in the moisture content range of 11.1% to 17.1% w.b., temperature range of 5°C to 40°C, and bulk density range of 722.1 to 800.6 kg m^{-3} over the frequency rage of 1 to 1000 kHz. Dielectric constant and loss factor both decreased with increasing frequency and increased with increasing moisture content, temperature, and bulk density. Second-order and third-order polynomial models can be used to describe the relationships between dielectric properties (dielectric constant and loss factor) and moisture content, temperature, and bulk density, with coefficients of determination higher than 0.96. If the dielectric properties and temperature are given, then the moisture content of buckwheat could be sensed well. This study offers helpful information for developing a moisture sensor for buckwheat from dielectric properties.

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