Moisture-Dependent Dielectric Properties of Pea and Black-Eyed Pea

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Abstract: In this paper, a cylindrical capacitor was used to measure the dielectric constant of seeds. By measuring the dielectric constant, the moisture content of grains may be predicted. Change in dielectric constant of pea and black eyed-pea was investigated as a function of moisture content. Results showed that the dielectric constant highly depended on moisture content at all frequencies. The best results were obtained at 1 MHz frequency for pea and black-eyed pea with R^2 of 0.994 and 0.999 respectively. This frequency can be used to calibrate the instrument for measuring the moisture content of pea and black eyed-pea.
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1. Introduction

Moisture content is the most important physical property of seeds that affects other seed attributes. For example, the coefficient of friction, density and mechanical properties of agricultural products change when the moisture content varies. Also, the optimum stage of harvesting severely depends on the moisture content of seed. Various methods have been developed to estimate the moisture content of agricultural materials. A typical method is oven drying technique, which is a destructive and time-consuming method. Microwave spectroscopy is a suitable technique for determining the moisture content of agricultural goods (Gradinarsky et al., 2006; Kraszewski et al., 1997). The moisture content can also be determined by using neutron moisture gauges, which exploit the dependency of neutron parameters on the average hydrogen concentration (Nagy, 1968).

Infrared and laser light absorption spectroscopy are applied for measurement of the surface moisture content in various substances (Edwards et al., 2001), but these methods need expensive instrument. Capacitive technique is a simple, rapid and low cost method that can be used to determine the moisture content of seeds and grains. Because of these advantages, capacitive sensor is used in precision agriculture. Li et al. (2003) measured moisture content of cookies using dielectric spectroscopy. They used concentric sensor head that had been designed for localized measurements. It had three electrically separated sensing electrodes that were used as a fringing field sensor, when combined with a driving plate, as a parallel-plate sensor. They used 6 volt, 10 Hz to 10 kHz frequency sweep signal and a divider circuit to measure the capacitance of sensor. They reported that at the higher frequencies the sensitivity was increased, so they selected 10 kHz to calibrate the system. They calibrated the system based on a linear model, where the functional dependence of capacitance on moisture content was determined. The system allowed for both online moisture content sensing and moisture distribution profile imaging.

Campbell et al. (2005) designed and developed a system based on capacitive sensor for monitoring bees passing through a tunnel that was able to distinguish between entering and exiting bees and provide information on the size and velocity of each bee. Jarimopas et al. (2005) designed and developed an electronic device with a cylindrical capacitive sensor to measure the volume of selected fruits and vegetables. Ragni et al. (2006) used a sine wave radio frequency oscillator with parallel plate capacitor sample probe to predict the quality of egg during storage period. They noted the suggested models enabled to classify samples of shell eggs. Afzal et al. (2010) estimated leaf moisture content by measuring the dielectric constant of leaves in five different types of crops. They carried out experiments on five field crops of maize, sorghum, capsular bean, white bean and sunflower. According to their results, type, amount of ions and the leaf thickness affected the capacitance and produced the error in this method. They reported that the coefficients of determination were higher at 100 kHz than at 1 MHz. They observed that the higher the leaf moisture, the more the data points were scattered around the best-fit line, although the scattering was more uniform at 1 MHz.

The objective of this study was to investigate the relationship between moisture content and dielectric constant of seeds and develop a non-destructive and rapid measuring method by using the capacitive sensor for estimating pea and black eyed-pea moisture content.

2. Materials and Methods

2.1. Sample preparation

The required quantity of pea and black eyed-pea was provided and cleaned to prepare samples at five levels of moisture content. At each level, about 80 g of seeds was provided. The initial moisture content of seeds was determined by oven method (level 3). In order to reach the higher moisture level, to prohibit gemmating, the seeds samples were exposed to saturated air in an isolated box at 30 ˚C for 18 hours (level 4) and 36 hours (level 5), respectively. To reach the lower moisture content level, the oven method was used at 60˚C for 24 hours (level 2) and 48 hours (level 1). After collection of samples, they were stored in a refrigerator at 4 ˚C for 72 hours.

2.2. Instrumentation

An instrument based on capacitive technique was designed and developed to measure the dielectric constant of seeds at various moisture contents (Figure 1). The instrument consists of a signal conditioning circuit, a 10-bit Microcontroller (ATMega 32) interfaced with a 16×2 LCD display and sinusoidal function generator (XR2206). Function generator produces an AC current with variable magnitude and frequency. The produced sine signal was fed to capacitive sensor and output signal from the sensor was sent to signal conditioning circuit. The final output voltage was measured by ADC unit of microcontroller and the capacitance and dielectric constant of sample was computed by microcontroller and results displayed on LCD. Specific software was developed by C − language for calculations.

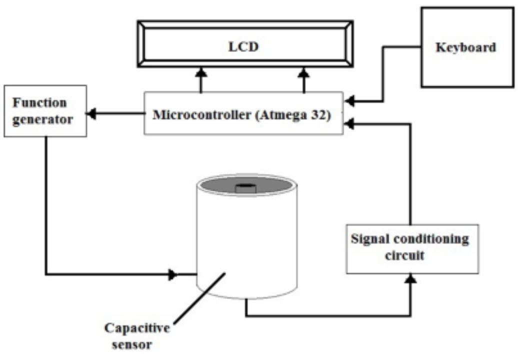

Figure 1. Block diagram of instrument for measuring the dielectric constant of seeds.

2.3. Cylindrical capacitive sensor

Figure 2 shows the capacitive sensor that was used in this research. The electrodes material was selected from aluminum. To avoid any occurrence of conduction, two polyethylene plates were used in construction of sensor. Each electrode was covered by a polyethylene layer with 1 mm thickness.

2.4. Dielectric Calculation

The capacitance of a cylindrical capacitor can be calculated by Eq.1.

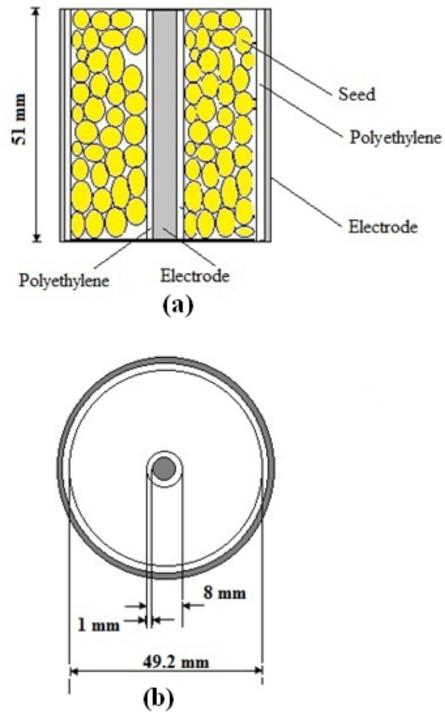

Figure 2. Cylindrical capacitive sensor filled with seed. (a) Section cut. (b) Top view.

$$C = \frac{2\pi \varepsilon_r \varepsilon_0 h}{Ln(\frac{b}{a})} \quad (1)$$

where; ε_r is the dielectric constant of material, ε_0 is the permittivity of air (8.85×10^{-12} F/m), h is the height of material, b and a are the radius of the outer and inner concentric cylinders.

It can be seen that each side of the polyethylene intermediary in Figure. 2 is in contact with the electrodes and seeds, so polyethylene layer became the series capacitance to the measuring system. The equivalent circuit diagram is shown in Figure. 3. In the diagram, C_{P1} and C_{P2} are the polyethylene capacitance, C_m is the measured capacitance, and C_{eq} is the equivalent capacitance of the sample (C_s) and air gap (C_{air}) that exists among seeds in the container, so seeds and air make a parallel capacitors. To measure the dielectric constant of polyethylene, a rectangular parallel plate capacitor with polyethylene dielectric material was constructed and its dielectric constant was calculated.

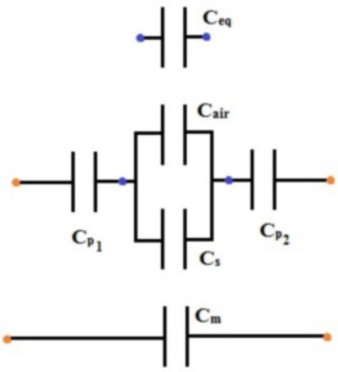

Figure 3. The equivalent circuit of capacitive sensor.

C_{eq} can be calculated by Eq. 2.

$$C_{eq} = \frac{1}{\frac{1}{C_m} - \frac{1}{C_{p_1}} - \frac{1}{C_{p_2}}} \quad (2)$$

The ratio of air gap volume to total volume of filled capacitor is defined as porosity (P) of seed, so the height of air gap in capacitor (h_{air}) is $P\times h$ and the height of sample (h_s) is $(1-P)\times h$. therefore:

$$C_{air} = \frac{2\pi\,\varepsilon_0 Ph}{Ln(\frac{b}{a})} \quad (3)$$

$$C_s = C_{eq} - C_{air} \quad (4)$$

$$\varepsilon_s = \frac{C_s Ln(\frac{b}{a})}{2\pi\,\varepsilon_0(1-P)h} \quad (5)$$

2.5. Experiments

Dielectric measurement of seeds was carried out at 5 levels of moisture content at 1 kHz, 10 kHz, 100 kHz, 500 kHz and 1 MHz frequencies. After electrical experiments, the moisture content of each sample was measured using oven method. The moisture content (*%MC_{db}*) was calculated on dry basis by Eq.6. Average porosity of pea and black eyed-pea are 0.435 and 0.41 respectively (Ayman et al., 2010; Unal et al., 2006) All measurements were performed in a laboratory with an average room temperature of 25 ˚C.

$$\%MC_{db} = \frac{w_w}{w_d}\times 100 = \frac{(w_i - w_d)}{w_d}\times 100 \quad (6)$$

where; w_i is the initial weight of sample, w_w is the weight of water in sample and w_d is the weight of dried sample.

Microsoft Excel 2007 was used to analyze data and determine the regression models between the studied attributes.

3. Results and Discussion

The measured moisture contents (*%db*) of pea and black-eyed pea specimens are presented in Table 1. Acceptable amplitude of variation is observed in moisture content of pea and black-eyed pea.

Table 1. Moisture content of prepared samples (*%db*).

Level	Pea	Black- eyed pea
1	4.34	5.3
2	6.15	7.78
3	9.73	12.11
4	17.17	19.68
5	19.35	20

The relation between ε_s and moisture content (%MC_{db}) of pea is presented in Figure 4. A high correlation is observed between ε_s and %MC_{db} at each frequency. At higher frequencies, the curves are smoother. The best equation that fitted to data is found as a quadratic function.

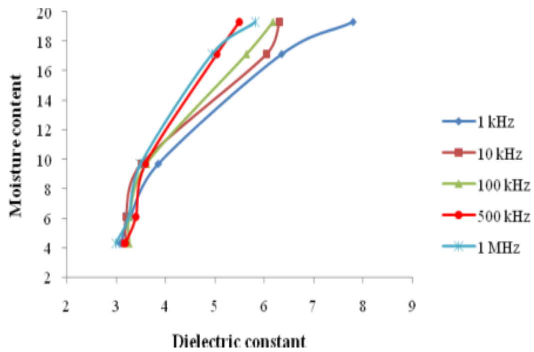

Figure 4. Change in moisture content versus dielectric constant of pea.

Results of regression analysis are presented in Table 2. The lowest value of coefficient of determination found at 10 kHz (R^2 = 0.963) which is an acceptable value. It means that quadratic function can fit into relation of ε_s - %MC_{db} as well.

Table 2. Results of regression analysis for prediction of pea moisture content.

Frequency	Equation	R²
1 kHz	$\%MC_{db}$ =-0.607 $\varepsilon_s{}^2$ + 9.646 ε_s -19.11	0.994
10 kHz	$\%MC_{db}$ = -1.823 $\varepsilon_s{}^2$ + 21.34 ε_s - 43.83	0.963
100 kHz	$\%MC_{db}$ = -1.325 $\varepsilon_s{}^2$ + 16.98 ε_s - 35.56	0.973
500 kHz	$\%MC_{db}$ = -2.095 $\varepsilon_s{}^2$ + 24.44 ε_s - 52.10	0.988
1 MHz	$\%MC_{db}$ = -1.653 $\varepsilon_s{}^2$ + 19.82 ε_s - 40.15	0.994

Figure 5 shows the relation between ε_s and moisture content ($\%MC_{db}$) of black-eyed pea. A high correlation is observed between ε_s and $\%MC_{db}$ at each frequency. The same results were obtained for black-eyed pea. Guo et al. (2007) reported a decrease in dielectric constant of apple when frequency of input signal had been increased. The best equation that fits to data is found as a quadratic function. Similarity between Figure 4 and Figure 5 reveals the fact that correlation between $\%MC_{db}$ and ε_s approximately is the same for black-eyed pea and pea.

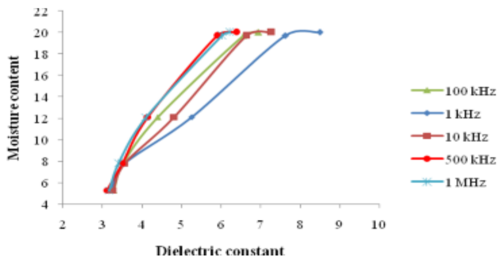

Figure 5. Change in moisture content versus dielectric constant of black-eyed pea.

Table 3. Results of regression analysis for prediction of black-eyed pea moisture content.

Frequency	Equation	R²
1 kHz	$\%MC_{db}$ = -0.210 $\varepsilon_s{}^2$ + 4.65 ε_s - 7.35	0.989
10 kHz	$\%MC_{db}$ = -0.998 $\varepsilon_s{}^2$ + 14.1 ε_s - 29.16	0.998
100 kHz	$\%MC_{db}$ = -0.797 $\varepsilon_s{}^2$ + 12.0 ε_s - 25.46	0.996
500 kHz	$\%MC_{db}$ = -0.998 $\varepsilon_s{}^2$ + 14.1 ε_s - 29.16	0.998
1 MHz	$\%MC_{db}$ = -1.084 $\varepsilon_s{}^2$ + 14.9 ε_s - 30.77	0.999

Results of regression analysis are presented in Table 3. The lowest value of R^2 was found at 500 kHz as 0.988. Although this value was the lowest one, from stand view of statistic, it is an indication of high correlation between ε_s and %MC. A homographic behavior exists between moisture content and dielectric constant of seed that is substantiated following:

The ratio of water weight to dry material weight of sample is defined as moisture content ($\%MC_{db}$) of seed, therefore:

$$w_w = \rho_w A h_w \tag{7}$$

where; ρ_w is the density of water, A is the base of cylindrical capacitor and h_w is the height of water in capacitor.

$$w_d = \rho_d A h_d \tag{8}$$

where; ρ_d is the density of dry material, A is the base of cylindrical capacitor and h_d is the height of sample's water in capacitor.

Substituting Eq. 7 and Eq. 8 into E.q 6 and setting ρ_w =1, the following equation is obtained:

$$MC_{db} = \frac{\rho_w h_w}{\rho_d h_d} = \frac{h_w}{\rho_d h_d} \tag{9}$$

The sample is composed of dry material and water, so these materials perform a pair of parallel capacitors, therefore:

$$\varepsilon_s = \varepsilon_d h_d + \varepsilon_w h_w \tag{10}$$

where; ε_s is the dielectric constant of whole sample, ε_d is the dielectric constant of dry material and ε_w is the dielectric constant of water.

$$h_s = h_w + h_d \tag{11}$$

where; h_s is the height of sample in capacitor.

From Eq. 10 and Eq. 11, it is obtained that:

$$\varepsilon_s = \varepsilon_d (h_s - h_w) + \varepsilon_w h_w \tag{12}$$

$$\varepsilon_s = \varepsilon_d h_s - \varepsilon_d h_w + \varepsilon_w h_w \tag{13}$$

$$\varepsilon_s = \varepsilon_d h_s + (\varepsilon_w - \varepsilon_d) h_w \tag{14}$$

From Eq. 9:

$$MC_{db} = \frac{h_w}{\rho_d h_d} = \frac{h_w}{\rho_d (h_s - h_w)} \tag{15}$$

By simplifying of Eq. 15, h_w is obtained as a function of MC_{db}.

$$h_w = \frac{MC_{db} \cdot h_s \cdot \rho_d}{1 + MC_{db} \cdot \rho_d} \tag{16}$$

By Eq. 13 and Eq.16 the following equation is obtained:

$$\varepsilon_s = \varepsilon_d h_s + \frac{MC_{db} (\varepsilon_w - \varepsilon_d) h_s \rho_d}{1 + MC_{db} \cdot \rho_d} \tag{17}$$

By substituting of $a = \varepsilon_d h_s$ and $b = (\varepsilon_w - \varepsilon_d) h_s \rho_d$, following homographic equation is obtained:

$$\varepsilon_s = a + \frac{b.MC_{db}}{1 + \rho_d \cdot MC_{db}} \quad (18)$$

Eq. 18 is a homographic function, therefore our claim is substantiated.

MS-Excel software does not have a homographic trend line option, but quadratic trend line can fit into homographic function reliably, because the shape of these functions is similar. For example if the equation $y = 0.25 + \frac{4x}{1 + 0.6x}$ is figured in Excel software and a quadratic trend line is fitted to it, the R^2 is obtained as 0.99 as shown in Figure 6.

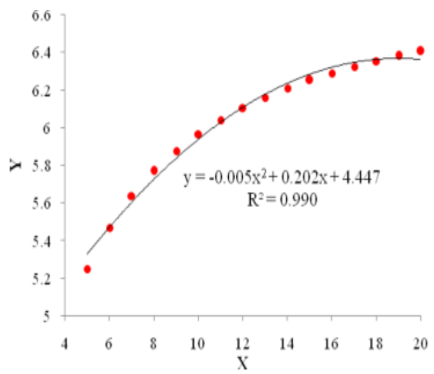

Figure 6. Curve of a typical homographic function and quadratic trend line.

4. Conclusion

To investigate change in dielectric constant of pea and black eyed- pea as a function of moisture content, an instrument was designed and developed. Relation between dielectric constant and moisture content was extracted and quadratic trend line was fitted to data. The results were obtained as expected. Dielectric constant changed as homographic function when moisture content varied. By this method, the moisture content of seeds and grains can be predicted reliably.

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