INTRODUCTION

Wheat is one of the main sources of food that is cultivated in most parts of the world. According to the FAO reports, the annual production of wheat in all over the world and Iran is 750 and 11.1 million tons in 2016, respectively (FAO, 2016).

Knowledge of the physical properties of agricultural products is useful in the design of agricultural machines. Determination of the physical properties of agricultural products results in the development of many instruments. These properties are important in the design and construction of machines used for planting and harvesting of agriculture products such as grains (wheat and barley), as well as transportation and processing (Baryeh, 2002). One of the new methods for separating seed from impurities is the use of electrostatic separators. In these separators, the differences in the electrical properties of the seeds are used to separate seeds that are not separable by conventional methods. These separators can separate seeds that have the same physical properties as the original seed, in addition to improve their germination percentage. The factors that affect the performance of this separation are the dielectric constant and electrical resistance of the particles. The dielectric or permeation coefficient is the property that a material exhibits in an electric field (Nelson & Trabelsi, 2017).

Information on the dielectric constant of grain has resulted in the development of a capacitance type grain moisture meter. Knowledge of the dielectric properties of seeds, grains, and other products is useful in many applications, including the prediction of the behavior of materials when exposed to electrical fields. The...
dielectric properties of food and agricultural products are basically used to describe the thermal behavior of materials when exposed to high-frequency electrical fields in dielectric thermal processes and the development of appropriate techniques for the rapid moisture content determination of agricultural products (Nelson & Bartley, 2000).

The moisture content of agricultural materials is an important indicator of the changes in their dielectric properties which is sensed through correlations with the electrical characteristics or dielectric properties, so obtaining these values in a certain moisture content determines the relationships between them (Nelson, 2010; Soltani, Alimardani, & Omid, 2010).

Several methods have been proposed to predict the moisture content of agricultural products. Among these methods, electrical measurement is a low cost, rapid, and effective technique and instruments based on this technique are subject to less errors that arise from nonuniform distribution of moisture and physical contact with the materials under test. The dielectric constant of many agricultural materials has been investigated. Furthermore, many researchers have described the correlation between moisture content and dielectric constant of grains and seeds.

A common method for determining moisture content is to dry the material in the oven, which may be a destructive and time-consuming method to remove all moisture. Although waveform spectrometry is a more appropriate method for determining the moisture content of agricultural materials, this method requires expensive and complex protocols (Edwards, Pirgozliev, Hare, & Jenkinson, 2001; Trabelsi, Kraszewski, & Nelson, 1998). Burton and Pitt (1929) developed a dielectric method for determining moisture content of four wheat cultivars. Casada and Armstrong (2008) measured the moisture content of wheat with a fringing field capacitive sensor. They extracted the linear calibration equations over a temperature range of 10°C to 30°C (Soltani et al., 2010). Prasad, Das, Ahmad, and Singh (2010) used dielectric constant of soybean at 2.45 GHz and 24°C to predict its moisture content. They introduced a quadratic equation that predict the moisture content as a function of temperature and dielectric properties without knowing the bulk density.

In this study, by developing a cylindrical capacitor in an electrical circuit, the electrical capacitance of wheat grain and cluster straw particles in two varieties (Chamran2 and Mehregan) in four levels of moisture content (8%, 14%, 20% and 25%) and five frequency levels (1, 10, 20, 100, 500 kHz) is measured and their dielectric constant is calculated.

2 | MATERIAL AND METHODS

The samples of wheat in the form of spikelet from two cultivars of Chamran2 and Mehregan were prepared from the farm of Lorestan Agricultural Research Center and were threshed and cleaned manually. Straw masses mostly included lemma and palea and less amount of straw, rachis, and pedicel. Initial moisture content of samples which included grain and straw were measured by oven method. The moisture content of the samples was increased by flooding method in distilled water in variable time (5–25 min) to obtain 5 levels of moisture (Khoshtaghaza & Meh dizadeh, 2006). The excess water was removed from the wetted samples at each interval. For moisture content measurement, a part of each sample was weighted and transferred to oven at 104°C for 48 hr. The remaining part was kept in refrigerator at 4°C for 72 hr for equalization.

2.1 | Circuit and measurement instrument design

To measure the dielectric constant of grain and straw at 5 levels of frequency at various moisture content, an instrument based on capacitive technique that include coaxial sample holder was designed and developed based on Soltani and Alimardani (2011b). The external electrode was an aluminum cylinder with 52 mm diameter, 3 mm thickness, and 100 mm height, and the internal electrode was an aluminum rod in the center with 10 mm diameter (Figure 1).
Inner surface of the cylinder electrode and the rod electrode was coated by polyethylene insulate. The assemble capacitor was installed to the circular base. To measure the capacitance of sensor, a voltage divider circuit was used (Figure 2). This capacitor circuit, in addition to a cylindrical capacitor had a function generator and a parallel specific capacitance that was placed to the circuit in form of series and an oscilloscope as the display of the values of voltage variations at different frequencies.

2.2 | Experiments

2.2.1 | Dielectric calculation

The cylindrical capacitor with a specified capacity was placed in a series circuit connected to an alternating source with a sine wave at 20 V and a frequency range of 1, 10, 20, 100, and 500 kHz (Figure 3). The voltage of capacitor was measured in different situations with dielectric of air (empty) and two wheat varieties Mehregan and Chamran at 5 levels of moisture contents (from 8% to 30%), and the straw of the cluster of these two varieties.

The capacitance of a cylindrical capacitor can be calculated by Equation (1).

\[
C = 2\pi\varepsilon_0\varepsilon_r h \ln \left(\frac{b}{a}\right)
\]  

where \(\varepsilon_0\) is the vacuum permittivity, \(\varepsilon_r\) is the dielectric constant of material, \(h\) is the height of material that is placed in the capacitive cylinder, \(b\) and \(a\) are the outer and inner radius of cylinder, respectively (Soltani & Alimardani, 2011b). It can be seen that on both sides of the cylinder, polyethylene coating is in contact with the electrode and the material with 1.5 mm thickness, so the capacitance of the polyethylene was measured in series with the system. The equivalent circuit diagram is shown in Figure 4.

In Figure 4, \(C_m\) is the measured capacitance, \(C_{P1}\) and \(C_{P2}\) are the polyethylene capacitance, and \(C_{eq}\) is the equivalent capacitance of the sample \((C_s)\) and air gap \((C_{air})\) that existed among the grain and straw mass in the container. \(C_{eq}\) is the sum of the capacity of the material and the air contained in its porosity space which is series with polyethylene coatings and can be calculated by Equations (2) and (3).

\[
C_{eq} = \frac{1}{\frac{1}{C_s} + \frac{1}{C_{P1}} + \frac{1}{C_{P2}}}
\]

\[
C_{eq} = C_s + C_{air}
\]
If the ratio of air gap volume to the total volume of capacitor that was filled by the material (wheat and straw) is defined as the porosity ($P$), then the height of air gap ($h_a$) is $P \times h$ and the height of materials in capacitor is $(1 - P) \times h$. Therefore, the capacitance of air and materials and their dielectric coefficient can be calculated with the following equations.

\[
C_{av} = \frac{2\varepsilon_0 Ph}{\ln \left( \frac{b}{a} \right)} \tag{4}
\]

\[
C_s = C_{eq} - C_{av} \tag{5}
\]

\[
\varepsilon_r = \frac{C_s \ln \frac{b}{a}}{2\varepsilon_0 (1 - P) h} \tag{6}
\]

### 2.2.2 Moisture content

The moisture content of samples was calculated on dry basis using Equation (7). Average porosity of wheat and straw are 0.45 were 0.64, respectively.

\[
\%MC_{db} = \frac{w_w}{w_d} \times 100 = \frac{(w_i - w_d)}{w_d} \tag{7}
\]

After measuring the moisture content of the samples (grain particles and straw) and transferring them to the cylindrical capacitor, the capacitor was placed in the circuit according to the Figures 2 and 3 so the electrical current and voltage of the capacitor were measured at 5 levels of moisture content for grain and 1 level for straw at 1, 10, 20, 100, and 500 kHz frequencies based on Guo, Yang, Zhu, Wang, and Guo (2013). The capacitance of circuit elements was calculated according to Equations (1)-(5). Therefore, the dielectric constant was measured at each moisture content and frequency according to Equation (6). Data analyses of the dielectric constant were carried out using a Factorial experiment in a Complete Randomized Design (CRD) with tree replications. Microsoft SAS (Ver. 9) was used for data analyses and Microsoft Excel 2016 was used to determine the regression models between dielectric constant and moisture content at different frequencies. The dielectric constant ($\varepsilon_r$) and the moisture content (Mc %) data of different materials ($V_1$, $V_2$, and $V_3$) in different frequencies were fitted to power, exponential, and polynomial models. The models were evaluated according to the statistical criterion $R^2$ for verifying the goodness of fit. The best model with the highest $R^2$ was selected to predict the $\varepsilon_r$ of materials as a function of the moisture content. Table 1 shows the symbols used for materials, moisture contents, and frequencies.
TABLE 2 Equations coefficients of the quadratic model of dielectric constant

| Frequency | $V_1$ | $V_2$ | $V_3$ |
|-----------|-------|-------|-------|
| $F_1$     | $a$   | $a$   | $a$   | 2.53 |
|           | $b$   | $b$   | $b$   | 0.57 |
|           | $c$   | $c$   | $c$   | 0.32 |
|           | $R^2$ | .99   | .99   | .99  |
| $F_2$     | $a$   | $a$   | $a$   | 1.21 |
|           | $b$   | $b$   | $b$   | 6.51 |
|           | $c$   | $c$   | $c$   | 6.02 |
|           | $R^2$ | .96   | .98   | .91  |
| $F_3$     | $a$   | $a$   | $a$   | 0.79 |
|           | $b$   | $b$   | $b$   | 4.29 |
|           | $c$   | $c$   | $c$   | 4.20 |
|           | $R^2$ | .91   | .98   | .94  |
| $F_4$     | $a$   | $a$   | $a$   | 0.99 |
|           | $b$   | $b$   | $b$   | 1.83 |
|           | $c$   | $c$   | $c$   | 2.49 |
|           | $R^2$ | .94   | .98   | .99  |
| $F_5$     | $a$   | $a$   | $a$   | 1.18 |
|           | $b$   | $b$   | $b$   | 1.92 |
|           | $c$   | $c$   | $c$   | 1.65 |
|           | $R^2$ | .99   | .98   | .99  |

3 | RESULTS AND DISCUSSION

The obtained dielectric constants of wheat grain and cluster straw samples at 25°C and four moisture content levels and frequency range from 1 to 500 kHz are shown in Figure 5. Results showed that increasing moisture content caused an increase in dielectric constant in both wheat grain and cluster straw. This increase was more significant at the frequency of 1 kHz, and the increase in frequency decreased this constant, and it was higher at higher moisture contents, especially for grains.

Results of the polynomial model of dielectric constant as a function of moisture content (% db) fitted by regression analysis to the experimental data in 5 levels of frequency using the general quadratic equation as: $\varepsilon_r = a(Mc_{(\%)} + b(Mc_{(\%)}^2) + c$ based on model parameters ($a$, $b$, and $c$) and $R^2$ are given in Table 2. Results show that at all frequencies, there is a high correlation between dielectric constant and moisture content. Factorial experiment in a randomized complete block design was used to analyse the result obtained from different moisture contents and frequencies. Table 3 shows the results of analyses of variance.

Results of the analysis of variance show that the dielectric constant in both wheat grain cultivars had a significant difference in 1% level, and this difference was most significant between grains and cluster straw. The effect of moisture content was significant at 1% level on the dielectric constant, and the frequency up to 500 kHz had significant effects on the dielectric constant. Interactions of parameters (material × moisture content, material × frequency, and moisture content × frequency) were also significant at 1% level.

Tables 4 and 5 show the effect of wheat and straw cultivars, moisture content, frequency, and their interactions on dielectric constant. The most changes in dielectric constant in the variable moisture content levels were for cluster straw particles with 2.25 and 27.48 in 8% and 25%, respectively. Maximum and minimum of grain's dielectric constant for both cultivars were in 25 Mc% and 8 Mc% equal to 27 and 3.7, respectively. The effect of increasing the frequency on the reduction of the dielectric constant in wheat grain particles (both varieties) was higher than on straw particles. Maximum and minimum values of dielectric constant in frequency varying were 32.33 and 4.3 for $V_1$ at 1 kHz and $V_2$ at 500 kHz, respectively.

These results were similar to the results of other researches. Nelson, Guo, Trabelsi, and Kays (2007) reported a reduction in the dielectric constant for wheat grain at a frequency range of 10–1,000 MHz. Kardjilova, Rangelov, and Hlavacova (2013) obtained similar results for spelled grains—*T. dicoccum* in the frequency range of 20–200 kHz in a moisture content of 11.4%; reducing the dielectric constant, conductivity, and capacitance of the particle. Guo et al. (2013) reported the increase of dielectric constant of straw by increasing Mc% from 10% to 20%. Similar results were obtained by Berber et al. (2001) in reducing the dielectric constant for coffee beans at 11%–12% moisture content and a frequency range of 500–5,000 kHz.

TABLE 3 Analyses of variance of wheat and straw cultivars dielectric constant ($\varepsilon_r$)

| Sources of variables | df | Sum of square | Mean square | $F$ value | $Pr > F$ |
|----------------------|----|---------------|-------------|-----------|----------|
| Materials            | 2  | 95.35         | 47.67       | 137.28    | <0.0001  |
| Moisture content     | 3  | 16,459.85     | 5,486.62    | 1,597.80  | <0.0001  |
| Frequency            | 4  | 11,410.04     | 2,852.51    | 8,213.31  | <0.0001  |
| Materials × Moisture | 6  | 403.60        | 67.26       | 193.68    | <0.0001  |
| Materials × Frequency| 8  | 1,085.18      | 135.64      | 390.57    | <0.0001  |
| Moisture × Frequency | 12 | 9,474.62      | 789.55      | 2,273.38  | <0.0001  |
| Materials × Moisture × Frequency | 24 | 1,660.35 | 69.18 | 199.20 | <0.0001 |
| CV                   | 4.44                                    |
TABLE 5 Comparison of the effect of wheat and straw cultivars, moisture content, and frequency on dielectric constant ($\varepsilon_r$)

| Material × Moisture   | $V_1M_1$ | $V_2M_1$ | $V_3M_1$ | $V_1M_2$ | $V_2M_2$ | $V_3M_2$ | $V_1M_3$ | $V_2M_3$ | $V_3M_3$ | $V_1M_4$ | $V_2M_4$ | $V_3M_4$ |
|-----------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Frequency             | $F_1$    | $F_2$    | $F_3$    | $F_4$    | $F_5$    |
| $V_1$                 | 3.93$^a$ | 3.84$^b$ | 2.25$^a$ | 7.7$^b$  | 6.52$^a$ | 5.28$^b$ | 14.51$^a$| 12.42$^b$| 19.1$^a$ | 29.76$^a$| 26.57$^b$| 27.48$^a$|
| $V_2$                 | 32.33$^a$| 28.03$^b$| 20.71$^a$| 16.49$^a$| 14.15$^a$| 19.3$^d$ | 10.65$^a$| 9.21$^b$ | 12.44    |          |          |          |
| $V_3$                 | 5.75$^a$ | 5.63$^b$ | 9.5$^b$  | 4.67$^b$ | 4.3$^b$  | 5.67$^b$ |
| Moisture × Frequency  | $M_1F_1$ | $M_2F_1$ | $M_3F_1$ | $M_1F_2$ | $M_2F_2$ | $M_3F_2$ | $M_1F_3$ | $M_2F_3$ | $M_3F_3$ |
| $M_1$                 | 12.75$^b$| 22.41$^a$| 2.57$^b$ | 4.46$^a$ | 9.15$^b$ | 11.7$^b$ | 1.85$^b$ | 3.65$^b$ | 5.87$^b$ | 8.17$^b$ |
| Note: Means with the same letter are not significantly different.

**4 | CONCLUSION**

Increasing moisture content in most agricultural products due to the presence of water molecules in the particles that have a high dielectric coefficient and high electrical conductivity reduces electrical capacities and increase electrical conductivity and their dielectric constant. This phenomenon is more significant in low frequencies. However, this process tends in straw to be faster than wheat grain particles, so making it difficult to separate straw and grain in electrical fields at straws with moisture content more than 12%.

**ACKNOWLEDGMENTS**

The practical experiments of this research were carried out in the Laboratory of physics department of Lorestan University, Khorramabad, Iran, and the authors are thankful to Prof. R. Sepahvand and the members of the laboratory for their contributions to the experiments of the laboratory for their contributions to the experiments. Again the authors would like to thank their colleagues at the Department of Agrotechnology, College of Abouraihan—University of Tehran.

**CONFLICT OF INTEREST**

The authors declare that they do not have any conflict of interest.

**ETHICAL APPROVAL**

This study does not involve any human or animal testing.

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How to cite this article: Jafari M, Chegini GR, Rezaeealam B, Shagayni Akmal AA. Experimental determination of the dielectric constant of wheat grain and cluster straw in different moisture contents. *Food Sci Nutr*. 2020;8:629–635. [https://doi.org/10.1002/fsn3.1350](https://doi.org/10.1002/fsn3.1350)