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ELECTRICAL PROPERTIES OF MUNG BEANS (Vigna Radiata L.)

ELEKTRIČNA SVOJSTVA MUNG PASULJA (Vigna Radiata L.)

Ján NOVÁK, Veronika ARDONOVÁ, Zuzana HLAVÁČOVÁ
Department of Physics, Faculty of Engineering, Slovak University of Agriculture in Nitra,
Tr. Andreja Hlinku 2,949 76 Nitra, Slovakia.
e-mail: jan.novak1@uniag.sk

ABSTRACT

This paper contains the results of measuring the electrical properties of mung beans (Vigna radiata L.) set. The conductivity and relative permittivity are the main parameters of dielectric material electrical properties. The electrical properties of mung beans samples had not been sufficiently measured, and the aim of this work was to perform the measurements of these properties. Measurements were performed under variable moisture content and the frequency of electric field from 0.1 kHz till 200 kHz for conductivity and in the range from 1 MHz to 16 MHz for relative permittivity, using RLC meter and Q meter, respectively. It was concluded that relative permittivity and conductivity increased with the increase of moisture content; resistivity, impedance, loss tangent, and relative permittivity decreased as the frequency of the electric field increased.

Key words: *relative permittivity, electric resistance, conductivity, mung beans.*

REZIME

Ovaj rad sadrži rezultate merenja električnih svojstava mung pasulja (Vigna radiata L.). Električna provodljivost i relativna permitivnost glavni su parametri električnih svojstava dielektričnog materijala. Električna svojstva uzoraka zrna pasulja nisu dovoljno istraživana, a cilj ovog rada bio je davse obavi merenje ovih svojstava. Merenja su obavljena pri različitim sadržajima vlage materijala i frekvenciji električnog polja od 0,1 kHz do 200 kHz za provodljivost i u opsegu od 1 MHz do 16 MHz za relativnu permitivnost, koristeći RLC metar i Q metar, respektivno. Zaključeno je da se relativna permitivnost i električna provodljivost povećavaju sa povećanjem sadržaja vlage; električnog otpora, impedancije, tangente gubitaka, a relativna permitivnost opada sa povećanjem frekvencije električnog polja.

Ključne reči: *relativna permitivnost, električni otpor, provodljivost, mung pasulj.*

INTRODUCTION

Mung bean or green gram (Vigna radiata L.) has been cultivated in India since prehistoric times and is believed to be a native crop of India (Dahiya et al., 2015). It is cultivated throughout Southern and Eastern Asia, Central Africa, some parts of China, South and North America and Australia, particularly for its protein-rich grains. Mung bean is a warm seasonal annual legume, grown mostly as a rotational crop with cereals like wheat and rice. This crop has been intensively researched in the work of Dahiya et al. (2015). Scattered data are available on various properties. Data on physical, chemical, food processing, and nutritional properties were collected for whole mung bean grains and reviewed to assess the crop's potential as food and to set research priorities. Results show that mung bean is a rich source of protein, in 100 g (14.6–33.0) g and iron (5.9–7.6) mg. Research on nutrient digestibility, food processing properties, and bioavailability is needed. Furthermore, the effects of storage and processing on nutrients and food processing properties are required to enable optimization of processing steps, for better mung bean food quality and process efficiency (Dahiya et al., 2015). The effect of moisture on geometric and mechanical properties was described in the paper of Unal et al. (2008). The crop's main advantages are that, as a legume, it does not require fertilization for nitrogen (Dahiya et al., 2015), and that it has a short growth cycle (75–90 days), requires little water and fits easily into crop rotations with cereals. It grows well under most adverse arid and semiarid conditions. Mung bean is considered a good source of protein (Gunathilake et al., 2016). Biochemical analyses in previously published studies reveal that mung beans and their processed products are rich in nutrients. The chemistry and technology of mung beans have been reviewed by

Gunathilake et al. (2016), who provided substantial information on the nutritional aspects, but only gave limited information on the processing of mung beans. Some publications also reviewed mung bean food products (Prabhavat, 1990; Singh and Singh, 1992; Gunathilake et al., 2016).

The research and determination of the physical properties of agricultural materials have resulted in the development of many instruments. The study of electrical properties is important for predicting the behaviour of a material in an electric field or for gaining knowledge of how the presence of material can influence the field or associated electrical circuit (Khaled et al., 2018). Electrical measurements conducted on food and agricultural materials are of fundamental importance in relation to the analysis of the quantity of absorbed water and dielectric heating characteristics. The research of electric properties is utilised in many technical applications. Measurements results are used for determination of moisture content, the surface level of liquid and grainy materials, controlling the presence of pests in seed storage, the quantitative determination of mechanical damage, and in many other cases (Priatková et al., 2011; Novák, 2018). Electrical impedance spectroscopy utilisation is described in a paper by Lopes et al. (2018). The planting depth accuracy can be determined also by electric properties measurement (Mapoka et al., 2019). Dielectric properties are affected by microwave and radio frequency heating systems; these attributes directly affect the electromagnetic arrangement and currents surrounding the materials, which can be used to control the

drying process (Al Faruq et al., 2019). The pulsed electric field can be used at the pre-sowing seed treatment

(Starodubtseva et al., 2018). Dielectric properties of materials represent an important part of electrical properties. The electric properties of many biological materials have already been observed. It was discovered that the electric properties of these materials are very dependent on material moisture content. Small amounts of adsorbed water can cause large changes in the electrical properties of hygroscopic materials. An extensive review of the literature on the dielectric properties of agricultural materials was published (Nelson et al., 2007). It includes several potential applications which are focused on the dielectric properties of such products. The electric properties of grains and seeds depend on their moisture content and on the frequency of the electric field. The dielectric properties of grains and seeds have been explored in certain frequency ranges, as these properties were of great significance for dielectric heating applications, for moisture measurement, or for process control detection (Nelson, 1999). The dielectric properties of most biological materials vary by frequency and temperature. In hygroscopic materials, they are also highly dependent on moisture content. Several aspects of the frequency dependence of dielectric properties have been included in the published review (Nelson et al., 2007). A study of the frequency dependence of dielectric properties of insects and grain in the frequency range from 250 Hz to 12 GHz has been documented (Nelson et al., 2007). This study defines the frequency range from 10 MHz to 100 MHz as the most promising frequency range for selective heating of rice weevils in wheat through differential energy absorption from an alternating electric field. For a more complete picture, however, similar data is necessary for the temperature dependence of dielectric properties. With recent progress in the practical application of microwave heating, a need for information on the dielectric properties of materials, to which such energy is applied, has been developed. While some information is available on the dielectric properties of grain, seed, and vegetables at lower frequencies (Nelson et al., 2007; Kertész et al., 2015), there is a scarcity of information on these properties at microwave frequencies. Therefore, the dielectric properties of several kinds of grain and seed have been measured at a few various microwave frequencies, and the dependence on moisture content has been taken into consideration. Nelson and Trabelsi (2017) gave a comprehensive summary of dielectric methods for measuring the moisture present in materials. Nelson (1999) discussed some methods of measuring the moisture content of the soil, too. One of these methods is the dielectric method. Resultant accuracy and temperature effects were also documented by Nelson (1999). The interest in the dielectric behaviour of biological materials increased with the spread of radio frequency heating techniques. Lawrence et al. (1992) discussed in detail the application of radio-frequency heating to good electrical conductors as well as poor electrical conductors. Bansal et al. (2016) studied the dielectric properties of rapeseed in the temperature from 20 °C to 60 °C and at the frequency range from 10 to 3000 MHz. The calculated penetration depth of the electromagnetic field of rapeseed at the frequencies for industrial, scientific, and medical applications (ISM frequencies) shows that at the given moisture content and temperature, it decreases with increasing frequency. Physical properties of mung bean grains and their relation with their chemical composition, particularly with moisture content, have been studied (Mangaraj et al., 2005; Yildiz, 2005; Unal et al., 2008; Gunathilake et al., 2016). This observation provided the basic lead for the design of many instruments and the application of dielectric heating to agricultural products.

Nomenclature:

m_1	mass of sample, kg
m_2	mass of dry sample, kg
j	imaginary unit
ε	permittivity of the material, F.m^{-1}
ω	angular frequency, s^{-1}
ε_0 = 8.854 × 10-12 F·m^{-1} – vacuum permittivity	
C	capacitance of a testing capacitor with a sample, F,
C_0	capacitance of empty testing capacitor without any interconnector capacitance, F
C_x	capacitance of interconnector, F
C_1	capacitance of tuning capacitor by resonance and without connection of testing capacitor, F
C_2	capacitance of tuning capacitor by resonance and by the connection of testing capacitor, F

MATERIAL AND METHOD

Measurements were carried out on samples of mung beans set. The samples were obtained from a local shop. The origin countries of samples are Argentina and China. The moisture content of samples was regulated by adding distilled water or by drying. Moisture content wet basis ω was determined according to standard by the following relation

$$\omega = \frac{m_1 - m_2}{m_1} 100\,\% \tag{1}$$

All measurements were performed at an air temperature of 20 °C and 60% air relative humidity. Bulk density ρV was determined by the mass of constant sample volume. The moisture content and bulk density of the samples are listed in Table 1.

Table 1. The moisture content and bulk density of mung bean set

ω (%)	ρ_V (kg.m^{-3})
4.3	827
6.0	763
12.1	738
13.9	719
16.6	700
19.8	689

Every material influences the electric field to which it is subjected. The relation between parameters of electromagnetic field and properties of material medium is described with conductivityσ, permittivity ε and permeability μ of this medium. Both parameters describe the electromagnetic properties of matter. The impact of moisture content on electrical properties at the frequency till 200 kHz and in the range from 1 MHz up to 16 MHz was observed in this paper.

The conductance G is the ability of a material to conduct electrical current, their unit is S. The conductivity is conductance in relation to proportions of material, the unit is S.m^{-1}. The resistance R and resistivity ρ are reciprocal values of the conductance and conductivity, respectively (Kertész et al., 2015). The complex value of the current density passing through the material in the case of an alternating electric field with intensity can be described as

$$i^* = \left(\sigma + j\,\omega\varepsilon\right) E^* \tag{2}$$

The paper of Nelson and Trabelsi (2017) deals with the measurement of these parameters. The permittivity of moist material must be complex.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{3}$$

The real part of complex permittivity is dielectric permittivity ε′. The coefficient of the imaginary part characterises losses in a dielectric. The dielectric properties of materials are generally formulated by relative complex permittivity:

$$\varepsilon_r^* = \frac{\varepsilon^*}{\varepsilon_0} = \frac{\varepsilon'}{\varepsilon_0} - j\frac{\varepsilon''}{\varepsilon_0} = \varepsilon_r' - j\varepsilon_r'' = \varepsilon_r'\left(1 - jtg\delta\right) \tag{4}$$

where:

$$tg\delta = \frac{\varepsilon_r''}{\varepsilon_r'} = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\,\varepsilon'} \tag{5}$$

is loss tangent of loss angle δ, which is the angle completing to $\pi/2$ phase difference between voltage and the current flowing through the dielectric.

Low-frequency electrical properties of mung samples were measured by an instrument GoodWill Instek LCR meter 821 (Good Will Instrument Co., Taiwan) at different frequencies using a four-electrode (tetrapolar) system. The sample was placed in the sensor with parameters: diameter d of the electrode is 37.8 mm, electrodes spacing ℓ is 49.2 mm, and mass of empty sensor 208.89 g. It has been measured capacitance C, resistance R, impedance Z, and loss tangent tgδ. Each property was measured in the frequency range from 0.1 kHz to 200 kHz, at all frequencies three times. The average value has been computed from these, and the standard deviation was calculated. To measure the dielectric properties of seed samples, a resonant method has been used. This method for measuring the dielectric properties of seeds and liquids in a frequency range from 100 kHz to 300 kHz was developed by Nelson et al. (2007). The capacitance of the testing capacitor was measured by the Q meter TESLA BM 560 (Tesla Brno, Czech Republic). By measuring the permittivity ε′ of the testing capacitor, the real capacitor can be considered as a lossless capacitor connected to active resistance in a parallel or serial configuration. The measurement goal is to determine the magnitude of capacitance of parallel or serial configuration of the capacitor with samples at a specific frequency. The Q meter was connected to the testing coaxial capacitor, which was used as a sample holder. The measurement was performed at the frequency range from 1 MHz to 16 MHz. Relative permittivity εr was calculated according to the following relations

$$\varepsilon_r = \frac{C - C_x}{C_o} \tag{6}$$

$$C = C_1 - C_2 \tag{7}$$

RESULTS AND DISCUSSION

From measured values are constructed graphical dependencies of electrical quantities on frequency and moisture content.

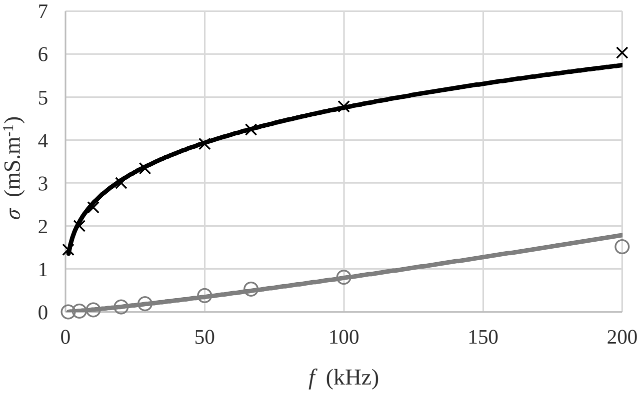

Fig. 1. Frequency dependence of samples conductivity at two moisture content (× – 19.8%; ○ – 4.3%)

The samples have a different moisture content ω and bulk density ρV, as shown in Table 1. The decrease of bulk density with an increase of moisture content was caused by the swelling of beans due to the absorption of moisture. Swelling of the beans also caused an increase in air gaps between the beans, which had reflected in the decrease in bulk density. For illustration in Fig. 1, the frequency dependencies of samples conductivity are presented. Electrical conductivity of mung bean samples increases in this frequency range. The conductivity is influenced by moisture content, and at the higher value of moisture content, the conductivity is higher at all measured frequencies. The following power model was used for both dependencies in Fig. 1

$$\sigma = \sigma_0 \left(\frac{f}{f_0}\right)^k \tag{8}$$

where:

σ0 – reference value of conductivity; for moisture content 4.3% - σ0 = 4 x 10-06 S.m^{-1}, for ω = 19.8% - σ0 = 0.0014 S.m-1, f0 = 1 kHz, k – constant; for ω = 4.3% - k = 1.177; for ω = 19.8% - k = 0.2726. A similar equation can be written also for resistance, impedance, and resistivity, but these quantities decrease with frequency. The coefficient of determination has a high value (0.9982, 0.9927). The change of resistance, impedance, and resistivity at low frequencies is significant, compared to the higher frequencies. Similar results have been obtained for other products, e.g., for various blueberry cultivars (Priatková et al., 2011), for sorghum grains (Audu et al., 2018). The relative permittivity εr in the function of frequency is shown in Fig. 2. The measurements indicate that seeds must be included in the most complex objects. It belongs to organic, heterogeneous, multi-component dielectrics. It was determined that the relative permittivity of mung beans decreases when the frequency of the electric field increases. The highest decrease was identified at a lower frequency of 3 MHz and lower moisture content of less than 10%. The minimal decrease can be observed at higher frequencies. In this case also the power functions best describe these dependencies. This relationship is caused by the dipole moment of water molecules and probably by the orientation of charged groups of macromolecules. In this case, orientation polarisation occurs in an electric field. This type of polarisation is highly dependent on frequency. Dipole macromolecules are not able to follow changes in the polarity of the electric field.

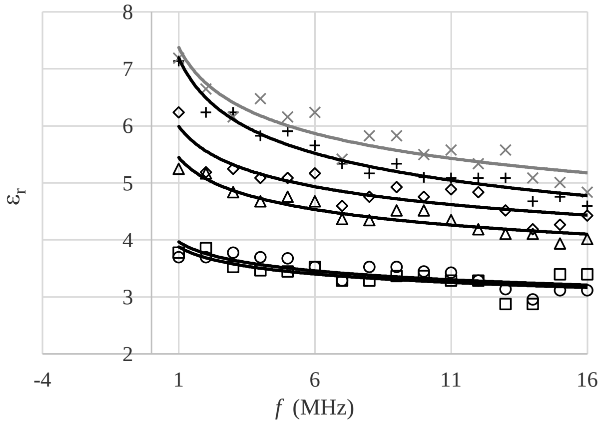

Fig. 2. The relative permittivity as a function of frequency at various moisture content (× – 19.8 %; + – 16.6%; ◊ – 13.9%; Δ – 12.1%; □ - 6%; ○ – 4.3%)

This power model was used for both dependencies.

$$\varepsilon_r = \varepsilon_{r0} \left(\frac{f}{f_0} \right)^k \tag{9}$$

where:

εr$_0$ – reference relative permittivity, k – constant, f$_0$ = 1 MHz.

The coefficients of regression Eq. (9) and coefficients of determination are in Table 2. Coefficients of determination have high values. The factors having the highest effect on these dependencies are also specified. The values of relative permittivity increase with the increase of samples' moisture content. This effect is the consequence of a very high magnitude of water relative permittivity in comparison to other seeds components.

Table 2. Coefficients of regression equation (9) and coefficient of determination

ω (%)	ε_{r0}	k	R^2
4.3	3.9717	-0.0772	0.6547
6.0	3.9486	-0.0882	0.7224
12.1	5.4438	-0.1021	0.8922
13.9	6.2415	-0.1255	0.8651
16.6	7.1907	-0.1483	0.9493
19.8	7.3718	-0.1275	0.8529

The effect of moisture content on relative permittivity is shown in Fig. 3.

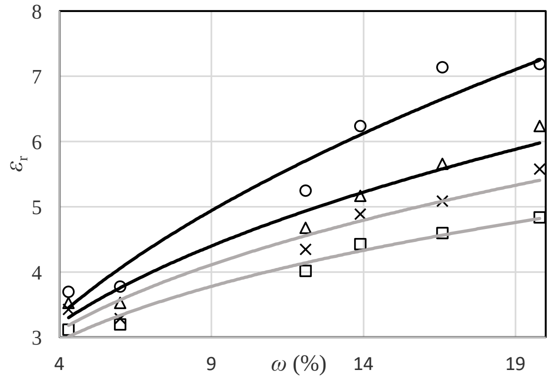

Fig. 3. Moisture content dependencies of relative permittivity for mung beans samples at different frequencies (○ – 16 MHz,Δ – 11 MHz, × – 6 MHz, □ – 1 MHz)

It is known that electric properties are also related to the bulk density of the material. Therefore, to ensure the definiteness of results, the bulk density values of samples have been introduced, too (Table 1).

The following power model was used for both dependencies in Fig. 3

$$\varepsilon_r = \varepsilon_{r0}\, \omega^k \tag{10}$$

Coefficients of regression Eq. (10) and coefficients of determination are displayed in Table 3.

Table 3. Coefficients of Eq. (10) and coefficient of determination

f (MHz)	ε_{r0}	k	R^2
1	1.7008	0.4855	0.9505
6	1.8746	0.3883	0.9537
11	1.9203	0.3467	0.9316
16	1.9201	0.3083	0.9742

Similar results for other biological materials were presented by other authors (Bansal et al., 2016; Nelson, 1999; Nelson et al., 2007; Lawrence et al., 1992). The low-frequency dependencies of loss tangent are shown in Fig. 4.

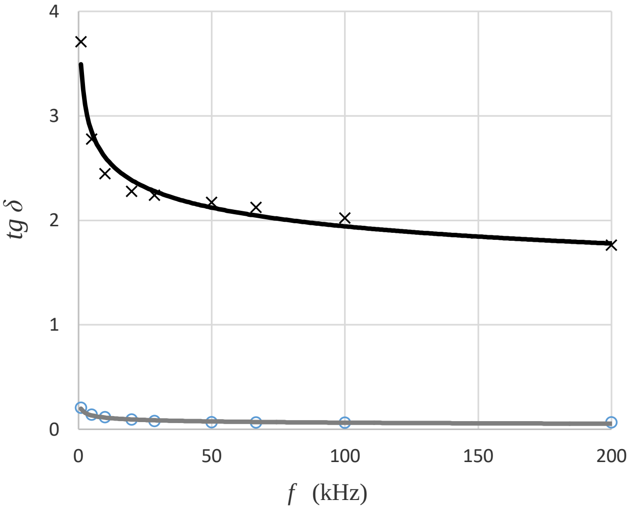

Fig. 4. Loss tangent versus frequency dependencies at two moisture content (× – 19.8 %; ○ – 4.3%)

Even in this case, the dependencies behaviour was modelled using the power function like Eq. (10). The coefficients of regression equation are:

at moisture content of 4.3% - reference value of loss tangent tgδ0 = 0.1976, coefficient k = -0.246 at moisture content of 19.8% - tgδ0 = 3.927, k = -0.127

Coefficient of determination has high values (0.9609; 0.9446). Loss tangent is decreased with frequency in this frequency range. At higher moisture content, dielectric losses in mung bean set are higher than at lower moisture content. This phenomenon is caused by the polarization of electrodes at low frequencies and high dipole moment of water molecules (Nelson, 1999; Schwan, 1968).

CONCLUSION

It has been found out that the resistance, impedance, resistivity, loss tangent decrease and conductivity of mung beans set increases with frequency, respectively, according to power function in the frequency range 0.1 – 200 kHz. The change of these electric properties at low frequencies is significant, compared to the higher frequencies. All these parameters are significantly influenced by the moisture content. The resistance, impedance, and resistivity decrease with moisture, while conductivity and loss tangent increase, respectively. It can be concluded that the relative permittivity of mung beans increases when the moisture content of samples increases and relative permittivity decreases as the frequency of the electric field increases at the frequency range from 1 MHz up to 16 MHz. The measurement results indicate that the most suitable frequencies of an alternating electric field for dielectric heating of mung beans are higher than 10 MHz. The relationships of the conductivity and relative permittivity of mung bean set samples provide the basis for the design of many commercial moisture-testing instruments. In the future, the performance of additional measurements at a wider frequency range would be desirable.

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