Frequency, moisture content, bulk density and hybrid effects on grain sorghum dielectric properties

E. E. Moura[1], P. A. Berbert[2*], E. F. Souza[2], R. F. Garcia[2], M. A. B. Molina[2], M. R. O. Oliveira[2]

(1. Brazilian Federal Institute of Education, Science and Technology, 29300-970, Cachoeiro de Itapemirim, ES, Brazil; 2. Northern Rio de Janeiro State University, Agricultural Engineering Laboratory, Av. Alberto Lamego 2000, 28030-602, Campos dos Goytacazes, RJ, Brazil)

Abstract: The interest in the dielectric properties of grains has been increasing over the years due to their potential utilization in advanced technologies such as the density-independent on-line estimation of moisture content in automatic control processes in grain drying operations. A capacitive sensor was used with a LCR meter to obtain a better understanding of the variation of relative permittivity and dielectric loss factor of four hybrids of grain sorghum in the frequency range from 75 kHz to 5 MHz, at 23 ℃ and 62% relative humidity. Curves that are presented illustrate the variation of these dielectric properties on moisture content (7% to 23% w.b.), bulk density (575 to 819 kg/m^3) and hybrid. The obtained results should provide a firm basis for future accurate, fast and non-destructive determination of grain moisture content and bulk density in automated industrial drying and storage processes.

Keywords: relative permittivity, loss factor, radiofrequency impedance

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1 Introduction

The majority of high-capacity grain-drying installations around the world are of the continuous-flow, high-temperature type, where the aim is, as far as possible, to produce a finished dry product after only one pass of the stock through the dryer. The retention time of the grain in a continuous-flow dryer depends on the initial moisture content of the grain, the drying-air temperature and airflow rate, the dimensions and shape of the grain, and the dimensions of the dryer (Brooker et al., 1992). Moreover, the moisture content of grain at harvest varies randomly and grain drying rate also varies considerably while it passes through the dryer, an indication that some under or over exposure of the grain in the drying compartment may lead to significant under or over drying (Stenning and Berbert, 1993; Liu and Bakker-Arkema, 2001). Over drying increases production costs by increasing fuel consumption and under drying may lead to serious storage problems.

For many years the control of continuous flow dryers was entirely manual, whereby the condition of the grain leaving the dryer was adjusted by the operator until the required value of moisture content was achieved. This was usually done by control of the discharge rate of the dryer, the other variables of airflow rate and air temperature having been predetermined, the first by the dryer manufacturer and the second usually by the operator, having regard for the eventual prospective use of the grain. The measurement of the moisture content was usually by means of one of the wide range of moisture meters available on the market. The control of discharge rate was, then, a matter for immediate decision by the operator who was predominantly influenced by the moisture

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***Corresponding author: Pedro Berbert,** Northern Rio de Janeiro State University, Agricultural Engineering Laboratory, Av. Alberto Lamego 2000, 28030-602, Campos dos Goytacazes, RJ, Brazil.

content of the emerging grain (Stenning and Berbert, 1993).

Wherever human intervention of this nature is required, particularly when the operator has numerous responsibilities of which supervision of the dryer is only one, there is scope for error. It can be seen, therefore, that the manipulation of grain dryer performance is a matter which can benefit greatly from the introduction of automatic control technology.

In order to reduce energy consumption and relieve the dryer operator from some demanding responsibilities of making decisions in difficult circumstances manufacturers have indeed introduced, at various times in the past forty years, automatic monitoring and control systems based on electrical or thermal methods of estimation of moisture content. In any automatic control system it is the measurement of the controlled variable which is the primary key to success, and regrettably the equipment currently available has not always led to the desired accuracy of control. The reasons for this have been discussed by other authors (Liu and Bakker-Arkema, 2001; Dufour, 2006), but the essential problems hinge on one or more of the following: (a) Although partial differential equation grain drying models based on the laws of heat and mass transfer can be found in literature, not all of the assumptions made in the derivation of such models are properly clarified, leading to fitting some lumped parameter models, which does not provide as accurate a prediction of the drying phenomena as required when a model based control algorithm for on-line control is used (Parry, 1985); (b) Where electrical resistance or capacitance based methods are employed, the restriction of being able to take only localized, and therefore usually not representative, readings of moisture content of the grain entering or leaving the dryer, is the difficulty; (c) Variation in the moisture content of the incoming crop is not normally sensed by the control system. Indeed, the moisture content of the drying crop is not evaluated until a considerable amount of drying has already been done, or is only detected when the grain finally exits the dryer, whatever type of moisture sensor is used. Early action to anticipate changes in the required amount of drying is therefore precluded, and (d) Variation of the grain bulk density (kg/m^3) of the measured samples under static conditions or fluctuations of the grain mass flow rate (kg s^{-1} m^{-2}) under continuous flow conditions can produce significant errors in moisture estimation (Meyer and Schilz, 1980; Berbert and Stenning, 1996a; Kraszewski et al., 1998).

Most of the above mentioned constraints for the development of smart dryers in which a controller automatically tunes the drying conditions such that the mean output moisture content reaches a value close to the set-point, can be overcome by the indirect estimation of grain moisture content through its dielectric properties (Berbert et al., 2007; McIntosh and Casada, 2008; Jafari et al., 2010; Kandala and Sundaram, 2010). At present, most grain moisture content determinations are made with electronic devices that measure an electrical property of the material that is dependent on its moisture content. These measurements are typically performed on randomly selected samples and under static conditions. However, for an automated drying system, it is desirable to monitor the moisture content continuously or on-line. For continuous sensing of moisture content of flowing grain, the more practical measurement method appears to be that utilizing the dielectric properties of the grain; more specifically its relative permittivity ε' and loss factor ε''. It is the high correlation of these parameters with moisture content that permits successful measurement of grain moisture content by most commercially available electronic moisture meters. The use of conductance or resistance-type moisture meters presents no reliability for conductivity and resistivity are susceptible to variation in moisture distribution in the grain sample and within the kernel. So, serious errors will be introduced if measurements are made on whole grains after recent drying or possible wetting of the crop in the field. This limitation could be overcome by grinding the grain but this would add bulk to the desirable compactness of the equipment. An additional problem concerning the use of conductivity for the indirect estimation of the moisture content of a stream of grain is the difficulty in achieving reproducible contact between the electrodes and the moving material. The dielectric properties of materials are best described in terms of the complex polarization mechanisms that appear when these materials are subjected to a sinusoidal field of angular frequency ω. The complex relative permittivity under sinusoidal conditions is conveniently expressed by $\varepsilon^* = \varepsilon' - j\varepsilon''$, where the relative permittivity ε' represents the ability of a material to store electric energy, and the loss factor ε'' characterizes the loss of electric energy in the material (Kraszewski, 1996).

Studies of the dielectric properties of cereal grains such as corn (Nelson, 1979; Sacilik and Colak, 2010), rice (Noh and Nelson, 1989; Prasad and Singh, 2007), wheat (Nelson and Stetson, 1976; Berbert and Stenning, 1996b), barley (Kim et al., 2003), sorghum (Moura et al., 2013) and oilseeds (Sacilik et al., 2006; Soltani et al., 2014) have been conducted over the last forty years, using either radiofrequency or microwave aquametry, a fundamental step towards the development of on-line density-independent models for moisture content estimation. Besides, the dielectric properties of foodstuffs (Sharma and Prasad, 2002; Wang et al., 2003; Mc Carthy et al., 2009), pharmaceuticals (Magee et al., 2013) and wood (Tomppo et al., 2009) are critical information whenever radiofrequency or microwave dielectric heating applications are considered for such materials.

In order to design a comprehensive capacitive sensor for on-line grain moisture content estimation in automatic control operations, dielectric data for a number of cereal grains, pulses, oilseeds and coffee are required. In fact, dielectric data for many agricultural products remain exiguous in the literature, and therefore there is a need for a database comprising these properties measured over a wide frequency range and under varying physical conditions, such as moisture content, bulk density and temperature. Such a database is considered useful in the derivation of bulk density independent dielectric models for on-line estimation of grain and seed moisture content, which relies on large data sets (Trabelsi, 2006). Of the major cereal crops produced worldwide only grain sorghum has not yet been fully characterized through its dielectric properties. Sorghum [*Sorghum bicolor* (L.) Moench] is an indigenous African grass with Ethiopia regarded as one of the sources of origin and the major centre of diversity for the species (Chala et al., 2011). The crop presents high water use efficiency for growing in high temperature and drought prone areas and due to its high tolerance to semi-arid environments and nutrient-poor soils it is capable of enduring subpar growing conditions (Pennisi, 2009; Wang et al., 2009). Sorghum is the fifth most important cereal crop in the world, in terms of both production (61.5 million tonnes) and harvested area (42.3 million ha) (FAOSTAT, 2013). Although its production is less than that of the other major cereal crops, it is nonetheless a staple for both humans (grain sorghum for starch) and livestock (sorghum for forage and silage), and is also grown for syrup and bio-ethanol production (sweet sorghum) (Sasaki and Antonio, 2009; Whitfield et al., 2012). Therefore, the object of the research work described in this paper is to measure the dielectric properties of static samples of four sorghum hybrids as a preliminary step towards the development of a density-independent method capable of evaluating its moisture content continuously, and on-line, at excitation frequencies in the range 75 kHz to 5 MHz, for moisture contents between 7% and 23% w.b.

2. Materials and methods

2.1 Sample container and measuring principle

The description of the sample container used to determine the dielectric properties of grain sorghum in this study can be found elsewhere (Berbert et al., 2002). The two parameters of the complex relative permittivity of the sample material, $\varepsilon^* = \varepsilon' - j\varepsilon''$, were calculated from measurements of the equivalent parallel capacitance (C_p, pF) and the conductance (G, Siemens) of the sample container, both empty and filled with a grain sample. Relative permittivity ε' and loss factor ε'' were calculated using Equations (1) and (2), respectively, where C_m is the measured capacitance of the sample container filled with grain, C_f is the capacitance associated with fringing fields and stray capacitances, G_m is the measured conductance, G_a is the conductance of the empty sample container, ω is the angular frequency of the applied electric field (Hz), and C_0 is the capacitance of the empty sample container. Detailed derivations of Equations (1) and (2) can be found in a previous paper (Berbert et al., 2001).

$$\varepsilon' = \frac{C_m - C_f - 2.1837}{5.7896} \quad (1)$$

$$\varepsilon'' = \frac{G_m - G_a}{\omega C_0} \quad (2)$$

2.2 Equipment and procedures

A Hewlett-Packard model 4285A Precision LCR Meter was used for measuring the dielectric properties of grain sorghum samples in the frequency range from 75 kHz to 5 MHz. The instrument can measure complex impedance, $|Z|e^{j\theta}$, and derived electric parameters of LCR components over the frequency range from 75 kHz to 30 MHz using test signal levels from 5 mV_{rms} to 2 V_{rms}. Measurements were taken with the voltage level set at 1.0 V_{rms} at intervals of 5 kHz from 75 kHz to 100 kHz; 100 kHz from 100 kHz to 1 MHz; 1 MHz from 1 MHz to 5 MHz. An Agilent 82357B USB/GPIB interface converter was used to provide a direct interface connection from the GPIB measuring instrument to a USB computer port. Automated data collection was performed using LabVIEW® software.

Four-terminal pair configuration was employed to minimize mutual inductance, contact resistance, and unwanted residual factors related to ordinary termination methods. Figure 1 shows the four-terminal pair measurement configuration (Hewlett-Packard, 1996) and a schematic diagram of the measurement setup is depicted in Figure 2.

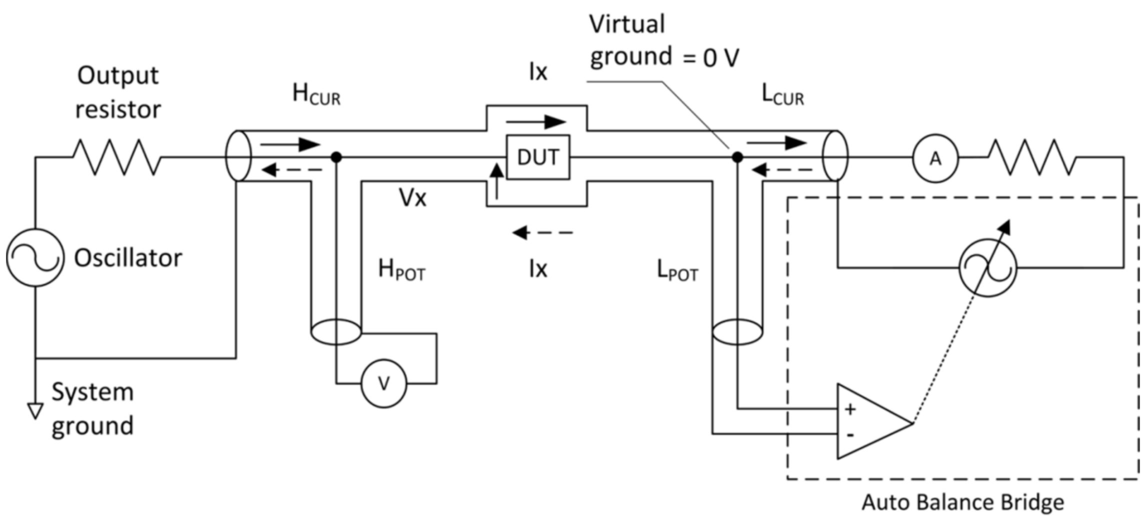

Figure 1 Simplified schematic diagram of a four-terminal pair configuration

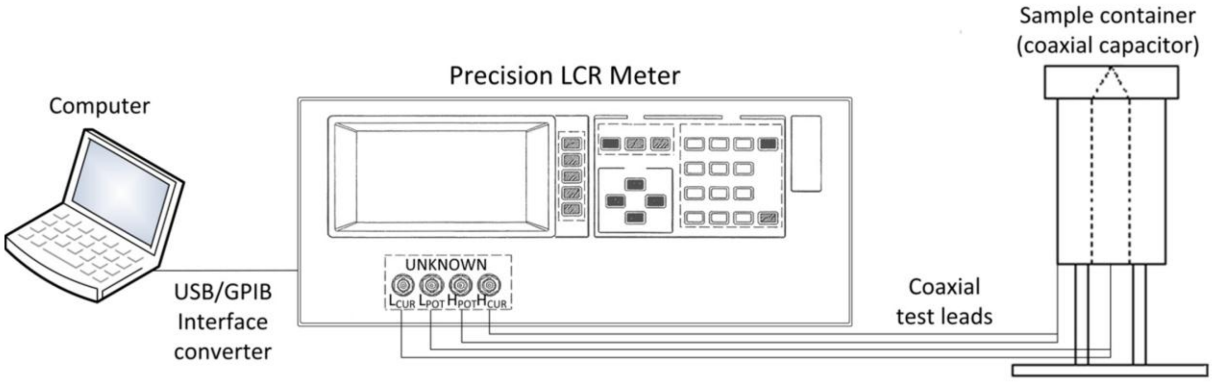

Figure 2 Schematic diagram of the measurement setup

The unknown terminals of the LCR meter consist of four coaxial connectors: H_{CUR} (high current), H_{POT} (high potential), L_{CUR} (low current), and L_{POT} (low potential). Current is supplied through the centre conductors and returns in an opposite direction through the outer shields, avoiding the generation of an inductive electromagnetic field around the cable and thus reducing the concern for mutual inductance (Hewlett-Packard, 1996). The four-terminal pair must convert to a two-terminal configuration near the sample container, and to accomplish this the electrical connection between the LCR meter and the sample container was made through 1 m coaxial test leads with 50 Ω silver plated BNC connectors at one end, and eyelet ring terminals at the other. To realize accurate measurements using the four-terminal pair technique, the centre conductors of the H_{CUR} and H_{POT} terminals must be connected to one electrode of the sample container, while both centre conductors of the L_{POT} and L_{CUR} terminals must be connected to the other electrode of the sample container; any other arrangement will result in an erroneous reading or none at all. The outer shields of the H_{CUR}, H_{POT}, L_{CUR}, and L_{POT} terminals must be respectively connected together at a point as near as possible to the point at which the sample container is connected to the test leads. The equipment virtual ground ($V \approx 0$ V) is associated with the centre conductors of the L_{CUR} and L_{POT} terminals, but it is the outer shields which are connected internally to the instrument's chassis, the effective ground. In circumstances where the centre conductors of one of the terminals are earthed, by connecting the outer electrode of the coaxial capacitor to the equipment's effective ground, the measured capacitance is just that between the inner and outer brass cylinders and the capacitor is screened from external effects. If, however, the inner electrode of the sample container was earthed, there would be an additional stray capacitance between the outer electrode and the surroundings in parallel with the original one. The voltage cables and current cables were twisted together as a pair to minimize errors caused by mutually induced emfs (Botos, 1979; Hewlett-Packard, 1996).

2.3 Grain sorghum samples

Certified seeds of two commercial grain sorghum (*Sorghum bicolour* (L.) Moench) hybrids, BRS 308 and BRS 310, and of two forage sorghum hybrids, CMSXS 769 (experimental) and BRS 655 (commercial), were used for dielectric properties measurements. Seed lots were obtained from the Maize & Sorghum Research Centre of The Brazilian Agricultural Research Corporation, EMBRAPA, after harvest in 2011. In order to maintain its original characteristics the sorghum, initially at 13% w.b. moisture content, was stored in polyethylene bags in a controlled-environment chamber at 4℃ prior to any conditioning. The moisture content of 0.6 kg sub samples of each hybrid was artificially raised from 13% to 23% w.b. in increments of approximately two percentage points moisture by adding the required amount of distilled water. For reduction of moisture content from 13% to 7% w.b., sub samples were dried for different periods of time at 38°C in a prototype laboratory dryer. Loewer et al.

(1994) described a method to determine weight reduction when a grain sample is dried. The method is based on sample initial weight and grain initial and final moisture contents. The weight gained when a grain sample is remoistened can be calculated using the same principles. After conditioning, the sub samples were sealed in air-tight Kilner jars and stored at 4℃, with periodic agitation for uniform moisture content distribution, for at least 15 d before they were drawn for measurements. All measurements were taken at room temperature, (22 ± 1)°C, and 62% ± 6% relative humidity (r.h.). Determination of moisture content was made on a wet basis and was carried out according to the International Rules for Seed Testing (ISTA, 2010). For moisture contents below 17%, duplicate ground samples of (4.5 ± 0.5) g were dried at 103 ± 2℃ for 17 h in a forced-ventilation oven. The two-stage method was employed when moisture content was higher than 17%. In this case, two subsamples of whole grain, each weighing (25 ± 1) g were predried at 130℃ for 5 min to 10 min, depending on moisture content. The partly dried material was then kept exposed in the laboratory for 2 h. The subsamples were then reweighed in their containers to determine the loss in weight. Immediately thereafter the two partly dried subsamples were separately ground and the moisture content was determined as prescribed (ISTA, 2010).

In order to assess the influence of bulk density when predicting sorghum moisture content from its dielectric parameters, the following procedure was employed, whereby five different levels of bulk density could be obtained for seed samples at the same moisture content level. Loose fill density was obtained by positioning the upper cylindrical container of a chondrometer above the sample holder, as shown in Figure 3a. After the cylindrical container (A) was filled with the sample, a slide (B) was withdrawn, allowing the sample holder to be filled as loosely as possible with no significant settling of the seeds. The upper cylinder was then removed and the surplus seeds were struck off from the top of the cell. By varying the internal diameter (D) (Figure 3b) of the lower edge of the funnel and the vertical dimensions H_1, H_2, and H_3, varying levels of settling of the grain inside the sample holder could be achieved, resulting in increased levels of bulk density.

To achieve a controlled reduction in the bulk density of the measured samples, the seeds were thoroughly mixed with predetermined amounts of expanded polystyrene beads, approximately the same shape and size of sorghum seed, which has a permittivity very close to that of air: 1.017 from 1 kHz to 1 GHz (Mathes, 1988; Bauccio, 1994). Polystyrene is also an extremely low loss material over the same frequency range, with a value for the loss factor ε'' of 0.0001, and as a result of this the material is unlikely to introduce spurious effects on the accuracy of loss factor measurements of samples of grain sorghum. Confirmation that the permittivity of the beads closely equates to that of the intergranular air, which the beads simulated, was obtained from preliminary tests in which the concentric sample cell was filled with the beads and capacitance measurements made at frequencies over the range 75 kHz to 5 MHz. The procedure described above provided the lowest levels of the bulk density achieved in the present work.

Bulk density was calculated by dividing the sample weight by the known volume of the sample container. As a rule three replications were performed at each combination of moisture content and bulk density levels, using the same sub-sample of sorghum seed each time. The dielectric properties calculated from the network output signals were averaged. Samples were allowed to reach room temperature before the electrical measurements were made. This was accomplished by removing the Kilner jars from refrigerated storage for at least 4 h prior to the beginning of each measurement sequence. For high moisture sorghum samples, moisture content was determined before and after the electrical measurements in order to verify the need for moisture corrections because of possible natural drying of the samples during measurements. In practice, the change of moisture was always negligibly small (less than 0.3

percentage point moisture), and so no correction was needed.

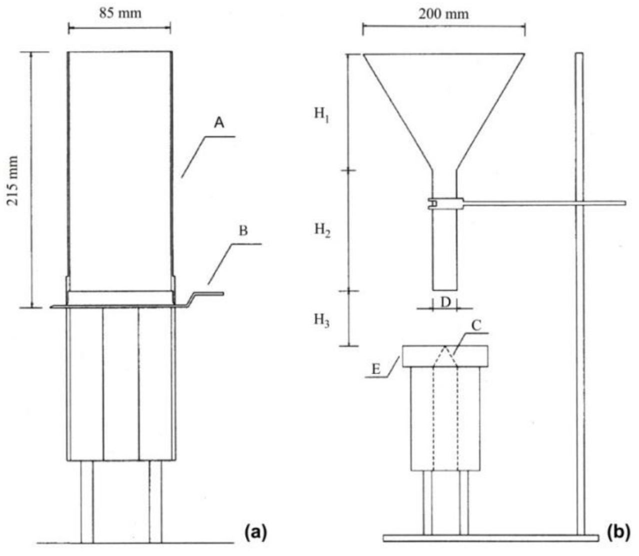

Figure 3 Arrangement for filling the sample holder to obtain loose fill bulk density (a) and to obtain increasing levels of bulk density (b)

2.4 Measurement uncertainties and errors in ε' and ε'' estimation

Accuracies in C_p and G measurements were determined following the procedures given by the Precision LCR meter manufacturer (Hewlett-Packard, 1996). These accuracies depend on the frequency of the applied field, the measured impedance of the device under test both empty and filled with the sample, integration time of the A/D converter, the oscillator voltage level, and cable length and temperature correction factors (Hewlett-Packard, 1996). The associated errors in ε' and ε'' were calculated introducing the uncertainties of the measured values of capacitance and conductance in Equations (1) and (2).

3. Results and discussion

3.1 Bulk density

Variation of bulk density with moisture content of the four sorghum hybrids on moisture content was determined experimentally using a chondrometer and the results are displayed in Figure 4. Points shown are average values of five replications at 22°C and 58% relative humidity. Best-fit curves obtained with a quadratic polynomial model, with coefficients of determination varying from 0.9252 (BRS 308) to 0.9946 (BRS 655), are also displayed. The experimental data confirmed the expected trend of decreasing bulk density with increasing moisture content for cereal grains (Brooker et al., 1992; Mwithiga and Sifuna, 2006; Subramanian and Viswanathan, 2007). It is also interesting to notice that the rate of changes in bulk density were greater at higher moistures than at lower moistures. Figure 4 shows that the slopes of the tangent lines to the curves are higher at points representing high moisture content samples as compared to the derivatives of these curves at points of low moisture content values. The decrease in bulk density with increase in moisture content observed in seeds of some species may result from an increase in size as the seed adsorbs water during the sorption phenomena. This behavior would give rise to a decrease in the quantity of seeds occupying the same bulk volume, and hence decreasing its density (Aviara et al., 1999).

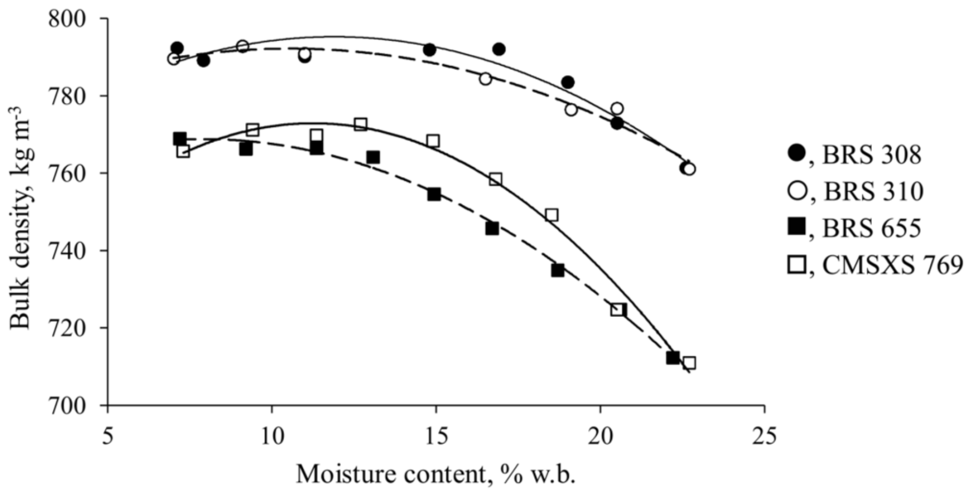

Figure 4 Effect of moisture content on bulk density of grain sorghum at 22°C and 58% r.h.

The range of bulk densities obtained at each level of moisture content for the four hybrids is shown in Figure 5. It can be seen that there was considerable scatter in the results at all moisture content levels studied. Grain sample mass varied from 0.316 to 0.450 kg, and bulk density values ranged from 575 to 819 kg/m^3. For samples at 23% w.b. moisture, the bulk density varied as much as 13% above the loose fill density for BRS 655, whereas for the other hybrids it varied up to 11%. The respective value for lower bulk densities, in relation to the loose fill value, was 12%. Fluctuations up to 8% in bulk density inside a grain dryer are not uncommon (DeVoe et al., 1985). Use of grain spreaders during bin filling produced bulk densities 13% greater in sorghum, 7% greater in wheat (Stephens and Foster, 1978) and 9% in corn (Chang et al., 1981), as compared to those produced by loading the bin from a central spout. However, the use of a grain stirrer during natural-air corn drying reduced the bulk density 5% (Wilcke and Bern, 1986). Therefore, the range of bulk densities achieved with the method described earlier is believed to represent the values that occur in practice.

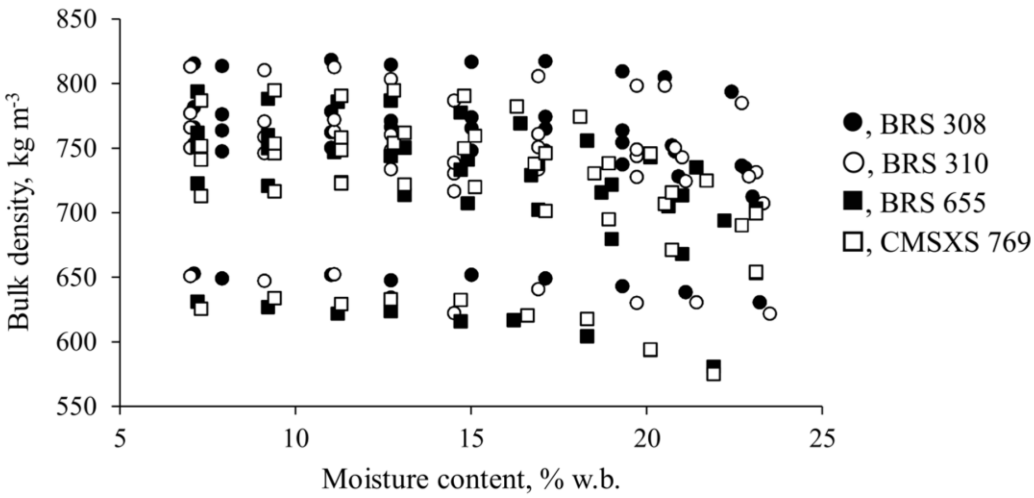

Figure 5 Bulk density of four hybrids of grain sorghum versus moisture content for different sample container filling methods at 22°C and 62% r.h.

3.2 Dielectric parameters of four grain sorghum hybrids

3.2.1 Effect of frequency

Permittivity (ε') and loss factor (ε'') were calculated for the selected frequency range and plotted for experimental sorghum CMSXS 769 at several moisture contents and similar bulk densities. The results are shown in Figures 6 and 7. The curves in these figures reaffirm that the magnitude of ε' and ε'' is heavily dependent on the frequency of the applied field and the grain moisture content.

As expected, the real component of the complex permittivity decreased as the frequency increased for grain of all moisture contents (Figure 6). The frequency dependence of ε' is greater at higher moisture levels due to the relatively high permittivity of water compared to the other major constituents of grain. An increase in the moisture content of a sorghum sample of given bulk density results in a greater amount of water within the sample holder which is available for dielectric polarization. In the lower frequency range the polarizations have time to form and to contribute their full amount to the permittivity. The dependence of the loss factor upon frequency was less regular than that of the permittivity (Figure 7). The slight increase in the loss factor of the three lower moistures at frequencies higher than 100 kHz (7.3% w.b.), 500 kHz (9.4% w.b.) and 1 MHz (11.3% w.b.) was questionable, because these samples are essentially lossless. For grain sorghum at 14.8% w.b. moisture ε'' always decreased with increasing frequency. Nonetheless, for high moisture grain sorghum, the shape of the curves shown in Figure 7 change to downward facing parabolas. The ascending portion of the curve at 17.1% w.b. moisture is seen to end somewhere between 100 kHz and 200 kHz, whereas for 20.1% w.b. moisture grain the highest ε'' value is reached at 400 kHz. The increase in the loss factor at these two higher moistures was probably not a result of relaxation mechanisms, but an exaggeration of the actual values caused by errors at those frequency ranges. Curves of very similar shapes were obtained for seeds of sorghum BRS 308, BRS 310, and BRS 655. These results are in agreement with those reported by Lawrence et al. (1989) in the measurement of the dielectric properties of soft red winter wheat. Some similar trends were also observed in studies with safflower seed (Sacilik et al., 2007).

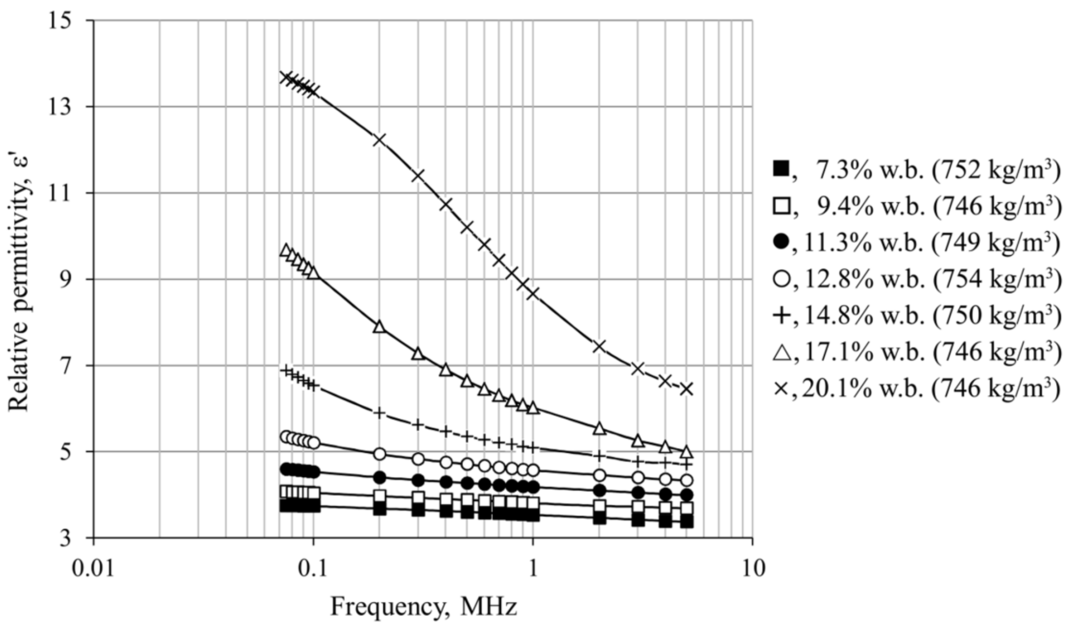

Figure 6 Variation of relative permittivity of CMSXS 769 grain sorghum, with frequency at indicated moisture contents and bulk densities at (23 ± 1) ℃ and 62% ± 7% r.h.

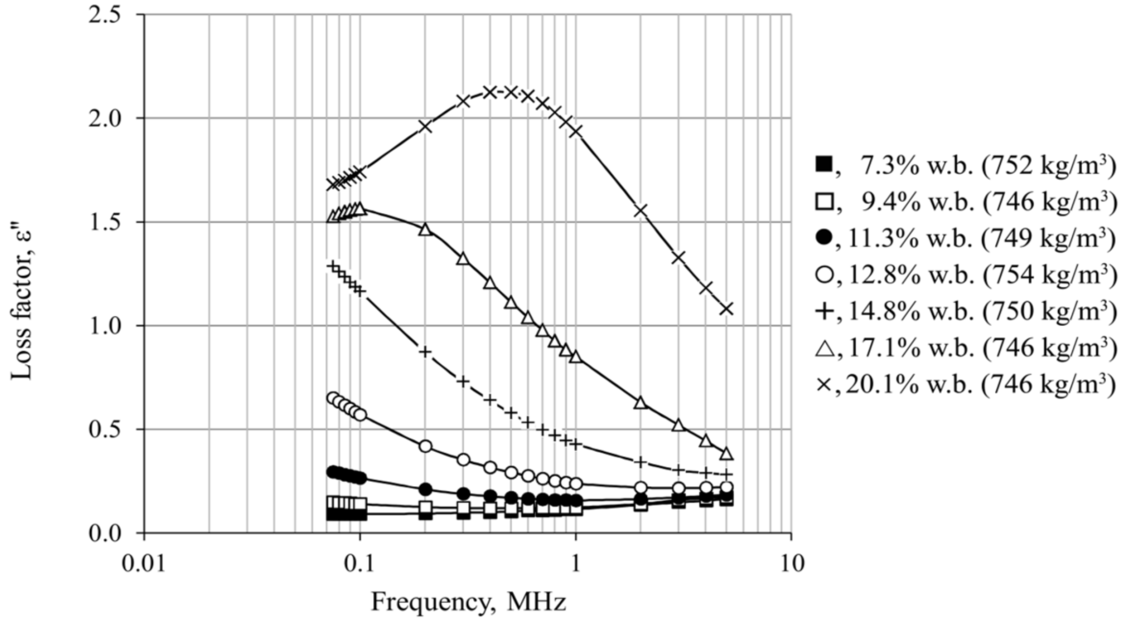

Figure 7 Variation of loss factor of CMSXS 769 grain sorghum, with frequency at indicated moisture contents and bulk densities at (23±1) ℃ and 62% ± 7% r.h.

3.2.2 Effect of moisture content

Permittivity increased with moisture content of grain sorghum at each frequency where measurements were taken. This is due to the relatively high permittivity of water in comparison to that of bone dry grain. The differences in permittivity with moisture for grains of the experimental sorghum CMSXS 769 at a bulk density level around 788 kg/m^3 are illustrated in Figure 8, where the regression lines and the experimental data points are shown for four values of frequency. It is apparent in Figure 8 that the change of slope of the cubic model occurs approximately at 13%-14% w.b. moisture for all studied frequencies, which indicates a possible region of dielectric dispersion. A similar behavior has been reported by Berbert et al. (2001, 2002) for common bean and parchment coffee, respectively, although the regions of dispersion for those products occurred in the range of moisture from 16% to 18% w.b., depending on the frequency. The regression of moisture content, M, on permittivity, ε', yielded the following polynomial equations, all with coefficients of determination r^2 very close to unity. At 5 MHz, a linear regression of moisture content on permittivity yielded a straight line: $\varepsilon' = 0.2200M + 1.9335$, with a coefficient of determination of 0.9956.

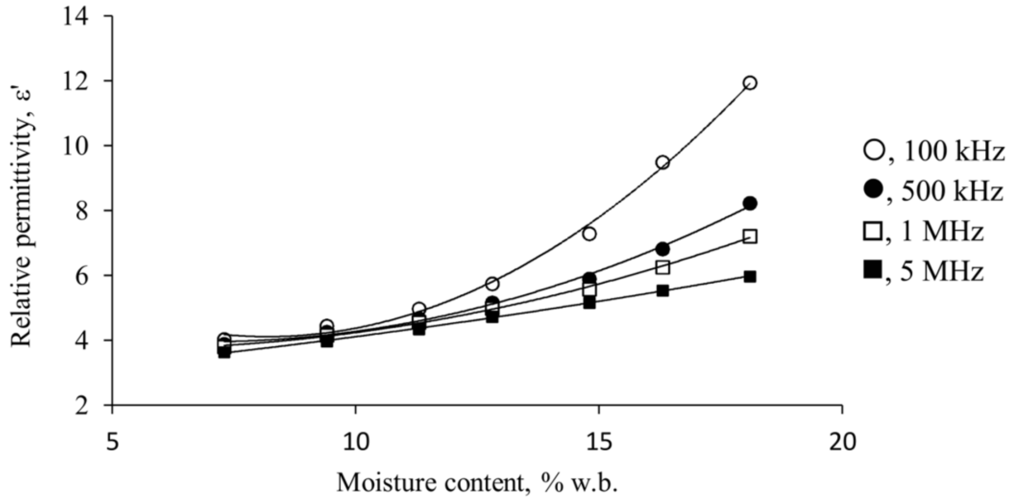

Figure 8 Variation of permittivity with moisture content at indicated frequencies of CMSXS 769 grain sorghum at bulk densities of (788 ± 7) kg/m^3, and (23 ± 1) ℃ and 63% ± 3% r.h.

$$\varepsilon'_{(100\ \mathrm{kHz})} = 0.0032M^3 - 0.0415M^2 + 0.1593M + 3.8832 \quad (r^2 = 0.9978) \tag{3}$$

$$\varepsilon'_{(500\ \mathrm{kHz})} = 0.0026M^3 - 0.0647M^2 + 0.7231M + 1.0438 \quad (r^2 = 0.9996) \tag{4}$$

$$\varepsilon'_{(1\ \mathrm{MHz})} = 0.0012M^3 - 0.0258M^2 + 0.3554M + 2.1182 \quad (r^2 = 0.9996) \tag{5}$$

$$\varepsilon'_{(5\ \mathrm{MHz})} = -0.0005M^3 + 0.0216M^2 - 0.0984M + 3.3687 \quad (r^2 = 0.9997) \tag{6}$$

Figure 9 shows the variation of the loss factor as a function of moisture content. The relationship was as regular as compared to the relationship between permittivity and moisture, and the regression of moisture content on loss factor also yielded cubic polynomial equations with high coefficients of determination, as follows:

$$\varepsilon''_{(100\ \mathrm{kHz})} = -0.0011M^3 + 0.0671M^2 - 0.9137M + 3.6328 \quad (r^2 = 0.9984) \tag{7}$$

$$\varepsilon''_{(500\ \mathrm{kHz})} = 0.0008M^3 - 0.0096M^2 - 0.0166M + 0.4453 \quad (r^2 = 0.9969) \tag{8}$$

$$\varepsilon''_{(1\ \mathrm{MHz})} = 0.0011\mathrm{M}^3 - 0.0247M^2 + 0.1831M - 0.3116 \quad (r^2 = 0.9980) \tag{9}$$

$$\varepsilon''_{(5\ \mathrm{MHz})} = 0.0007\mathrm{M}^3 - 0.0187M^2 + 0.1728M - 3.3496 \quad (r^2 = 0.9992) \tag{10}$$

Figure 9 shows the regression lines of the above mentioned best-fit equations and the experimental data points for four values of frequency. It can be observed the existence of some inconsistencies on the loss factor values obtained for grain in the lower moisture content range (7.3% to 11.3% w.b.). For instance, for the same moisture content, there are some values of ε'' which are higher at higher rather than lower frequencies. The same inconsistencies on the dependence of ε'' upon moisture content and exploratory explanations as to why these inconsistencies appear mainly in ε'' estimation were mentioned in earlier works (Nelson and Stetson, 1976; Lawrence et al., 1998).

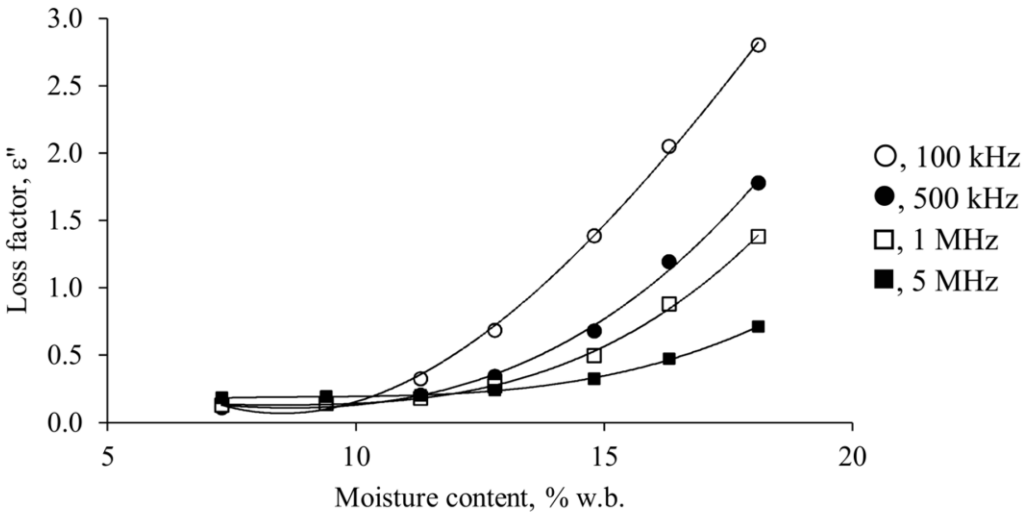

Figure 9 Variation of loss factor with moisture content at indicated frequencies of CMSXS 769 grain sorghum at bulk densities of (788 ± 7) kg/m^3, and (23± 1) ℃ and 63% ± 3% r.h.

Figure 9 Variation of loss factor with moisture content at indicated frequencies of CMSXS 769 grain sorghum at bulk densities of (788 ± 7) kg/m^3, and (23± 1) ℃ and 63% ± 3% r.h.

As was the case of the variation of permittivity with moisture, it can also be noted that at certain values of frequency, 500 kHz to 5 MHz, there occurs a change in the slope of the curves representing the variation of ε'' on moisture at 15% w.b., confirming a region of possible dielectric dispersion. Noticeable changes in the slopes of the ε'' *vs* moisture curves for common bean (Berbert et al., 2002) and parchment coffee (Berbert et al., 2001) have occurred at somewhat higher values of moisture, i.e., from 16% to 18% w.b., and from 15% to 16% w.b., respectively. As has been pointed by Berbert et al. (2002) the changes in permittivity and loss factor as a result of changes in moisture content were greater at lower frequencies than at higher frequencies.

As pointed out, the observed changes in slope of the curves representing the variation of ε' and ε'' on moisture content occurred at 13%-14% and 15% w.b., respectively. These changes are generally considered an indication of changes in the binding forces that exist between a monolayer of water molecules bound to the surface of the cells that form the walls of the capillaries within the grain (strongly bound water) and between adsorbed water molecules and molecules of water vapor, i.e., less tightly bound water or free water molecules (Kraszewski, 1996). If the above assumption is correct, the change in slope of the equilibrium moisture content curve for grain sorghum should occur at the same moisture interval indicated by the dielectric dispersion. Indeed, by determining the 20°C isotherm for the grain sorghum CMSXS 769 from 40% to 80% r.h., the change in slope occurred at 13% w.b. and the equilibrium relative humidity was 65%. For the lower portion of the isotherm, 40% to 65% r.h., the regression of moisture on relative humidity (r_h) yielded a straight line (M = 0.1046 r_h + 6.16) with a coefficient of determination of 0.9895. The corresponding results for the interval 65% ≤ r_h ≤ 80% were M = 0.2220 r_h – 1.52, with a coefficient of determination of 0.9891. The dielectric parameters of grain sorghum from the other three hybrids were similarly influenced by variations in frequency and moisture content.

3.2.3 Effect of bulk density

Results of the measurements of permittivity and loss factor of grain sorghum at 1.0 MHz as they vary with bulk density for BRS 310 are shown in Figure 10 and Figure 11, respectively. All measurements were taken in a room where the temperature was (22 ± 1) ℃ and the relative humidity was 58% ± 5%. For a given sample of sorghum at a given moisture content, functions of the dielectric properties appear to be nearly linearly related to bulk density over normal density ranges and have positive density coefficients. Considering that, theoretically, a line representing the relationship between ε' and ρ converges to a point whose Cartesian co-ordinates are very close to (0,1), linear regressions were performed to relate relative permittivity to bulk density values for the whole moisture content range studied, and the results are shown in Figure 12. So, when the sample container is empty and ρ has a value of 0 kg/m^3, the permittivity approaches a value very close to unity, 1.0006, which is the established value of the permittivity of air (Kraus and Carver, 1973). The linear equations relating permittivity and bulk density for moisture contents in the range from 7.0% to 23.1% w.b. and their coefficients of determination are shown in Table 1.

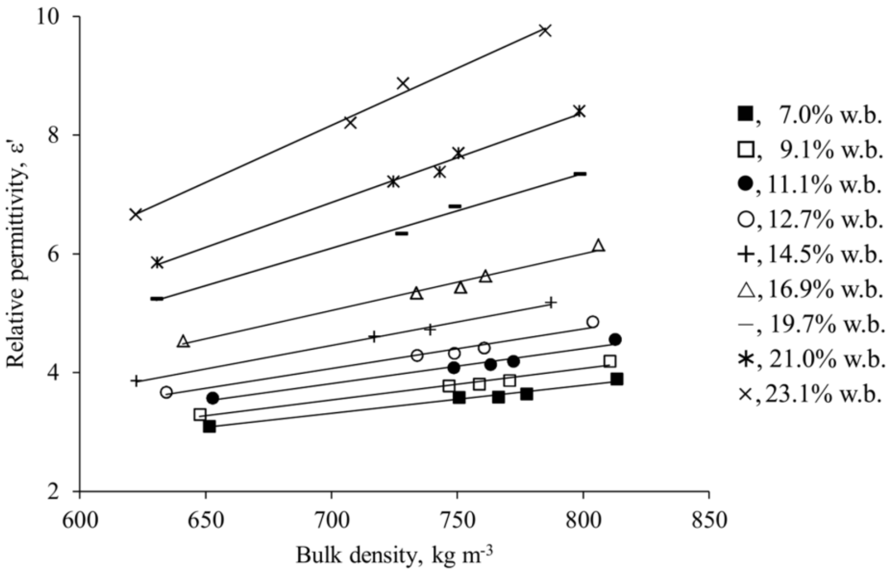

Figure 10 Variation with grain bulk density of the relative permittivity of grain sorghum, BRS 310, at indicated moisture contents, 1 MHz, (22 ± 1) ℃ and 58% ± 5% r.h.

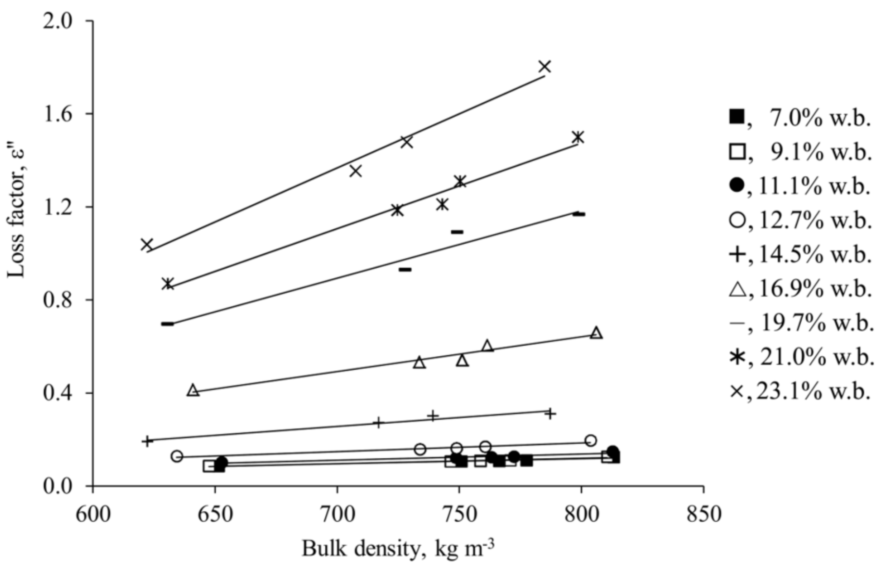

Figure 11 Variation with grain bulk density of the loss factor of grain sorghum, BRS 310, at indicated moisture contents, 1 MHz, (22 ± 1) ℃ and 58% ± 5% r.h.

Theoretically, a family of straight lines relating ε'' and ρ should converge to a point whose Cartesian co-ordinates are very close to (0,0), i.e., when the sample container is empty, the loss factor approaches a value very close to zero, since air is considered a lossless substance. Those straight lines relating loss factor and bulk density are shown in Figure 13, and Table 2 lists the linear equations relating loss factor and bulk density for moisture contents in the range from 7.0% to 23.1% w.b.

The slopes of the straight lines representing the variation of the permittivity and loss factor with varying bulk density increases as moisture content increases. This is evidence that the influence of bulk density on the dielectric parameters is enhanced by moisture. All these findings are in accordance with results presented by Meyer and Schilz (1980) and Berbert et al. (2002).

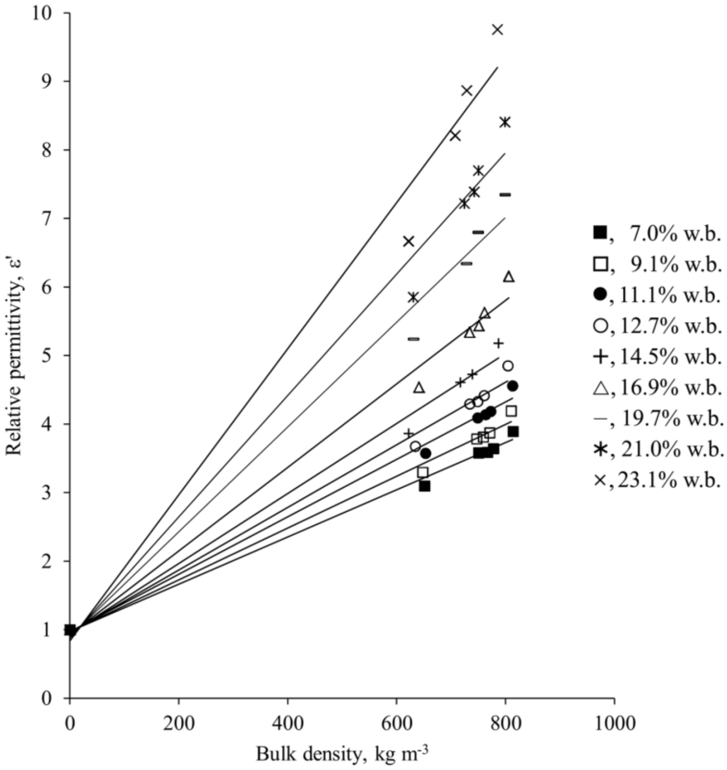

Figure 12 Variation with grain bulk density of the relative permittivity of grain sorghum, BRS 310, at indicated moisture contents, 1 MHz, (22 ± 1) ℃ and 58% ± 5% r.h., including Cartesian co-ordinates (0, 1)

Table 1 Summary of linear regression analysis* of data relating the relative permittivity ε' and bulk density ρ for grain sorghum, BRS 310, at indicated moisture contents, (22 ± 1) ℃ and 58% ± 5% r.h.

Moisture content, % w.b.	Regression equation	Coefficient ofdetermination r^2
7.0	$\varepsilon' = 0.0034\,\rho + 0.9750$	0.9947
9.1	$\varepsilon' = 0.0038\,\rho + 0.9707$	0.9938
11.1	$\varepsilon' = 0.0042\,\rho + 0.9687$	0.9936
12.7	$\varepsilon' = 0.0046\,\rho + 0.9558$	0.9911
14.5	$\varepsilon' = 0.0051\,\rho + 0.9440$	0.9894
16.9	$\varepsilon' = 0.0061\,\rho + 0.9313$	0.9885
19.7	$\varepsilon' = 0.0076\,\rho + 0.8985$	0.9848
21.0	$\varepsilon' = 0.0089\,\rho + 0.8699$	0.9825
23.1	$\varepsilon' = 0.0107\,\rho + 0.8348$	0.9778

* Regression equations were obtained considering that the lines converges to (0,1)

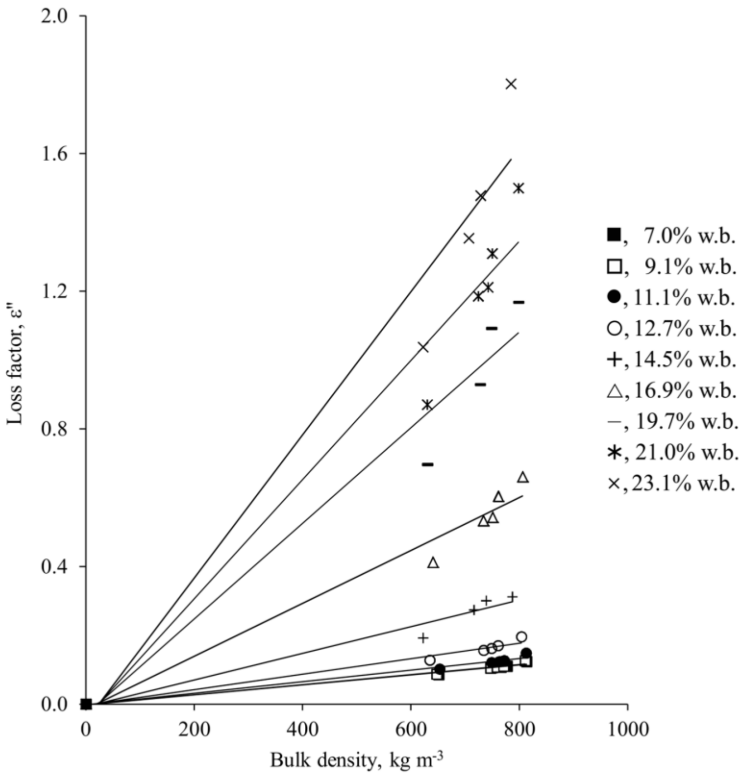

Figure 13 Variation with grain bulk density of the loss factor of grain sorghum, BRS 310, at indicated moisture contents, 1 MHz, (22 ± 1) ℃ and 58% ± 5% r.h.

Table 2 Summary of linear regression analysis of data relating the loss factor ε'' and bulk density ρ for grain sorghum, BRS 310, at indicated moisture contents, (22±1) ℃ and 58% ± 5% r.h.

Moisture content, % w.b.	Regression equation	Coefficient of determination r^2
7.0	ε'' = 0.0001 ρ – 0.0017	0.9883
9.1	ε'' = 0.0001 ρ – 0.0015	0.9846
11.1	ε'' = 0.0002 ρ – 0.0018	0.9834
12.7	ε'' = 0.0002 ρ – 0.0032	0.9798
14.5	ε'' = 0.0004 ρ – 0.0075	0.9631
16.9	ε'' = 0.0008 ρ – 0.0146	0.9670
19.7	ε'' = 0.0014 ρ – 0.0310	0.9543
21.0	ε'' = 0.0017 ρ – 0.0404	0.9557
23.1	ε'' = 0.0021 ρ – 0.0493	0.9484

* Regression equations were obtained considering that the lines converges to (0,0)

3.2.4 Effect of sorghum hybrid

Sorghum hybrid also had some effect on the dielectric properties, and its influence upon ε' and ε'' is shown in Figure 14 and Figure 15, respectively, for samples at 15% moisture and an average bulk density of (745 ± 5) kg/m^3. Permittivity varied from 4.90 to 5.39, while the loss factor varied from 0.3685 to 0.6070 at 0.5 MHz, 22 ℃, and 65% relative humidity. These variations correspond to relative changes of 10% in permittivity and 64% in loss factor. It can be seen in Figures 14 and 15 that the highest values of permittivity and loss factor occurred for the BRS 655 and CMSXS 769, whereas the lowest corresponding values were obtained with the BRS 308 and BRS 310, in the whole range of frequencies studied. The shapes of the curves representing the variation of loss factor on frequency were as regular as those representing the variation of permittivity on frequency for the four hybrids.

Although sorghum varieties may differ in their chemical analysis, it is unlikely that a slight change in chemical composition within different varieties may affect significantly the dielectric properties since most organic compounds are nonpolar. The effect of sorghum hybrid on ε' and ε'' values may be accounted for by the differences in physical properties of the kernels associated to each hybrid. According to Kupfer (1996) at higher frequencies the size of the grains within bulk samples of granular materials influences absorption and scattering of the electromagnetic field, thus affecting their dielectric properties. For similar values of bulk density, the measured values of capacitance and conductance increased as a result of larger grain dimensions, thus increasing ε' and ε'' values. Indeed, the largest kernel dimensions (length ×width × thickness) occurred for the BRS 655 (5.02 mm × 4.74 mm × 2.65 mm) and CMSXS 769 (4.90 mm × 4.18 mm × 2.67 mm) whereas the smallest corresponding values were obtained with the BRS 308 (3.80 mm × 3.48 mm × 1.95 mm) and BRS 310 (3.65 mm × 3.32 mm × 1.96 mm).

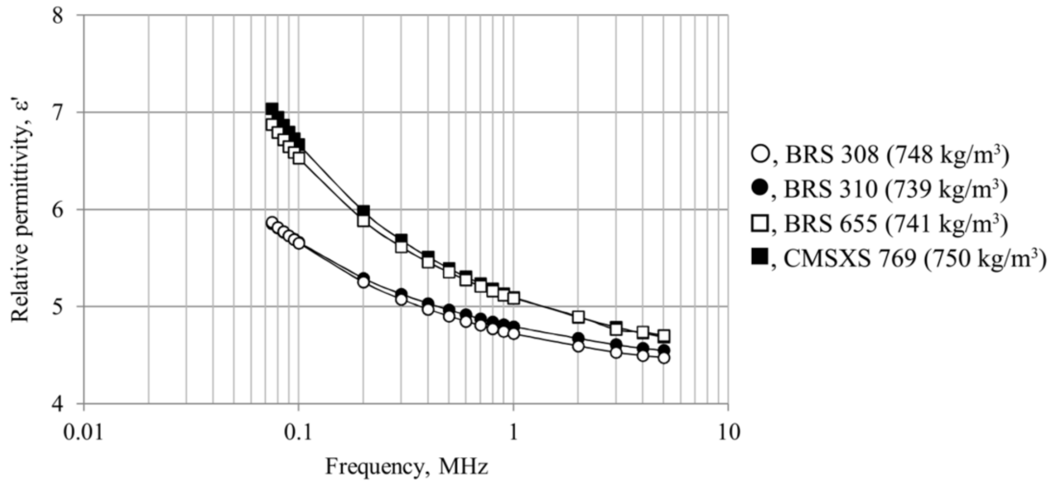

Figure 14 Effect of hybrid type upon the permittivity of grain sorghum at 15% w.b. moisture, 22 ℃, 65% r.h., and indicated values of bulk density

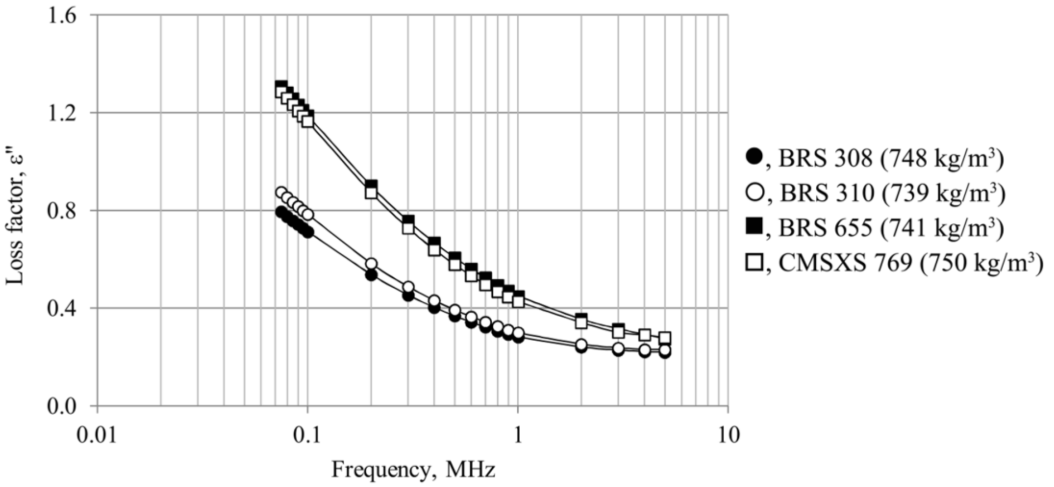

Figure 15 Effect of hybrid type upon the loss factor of grain sorghum at 15% w.b. moisture, 22 ℃, 65% r.h., and indicated values of bulk density

3.3 Comparison with published data

Direct comparison of the results described here with published data is rather difficult because of differences in variety, bulk density, and temperature. Nonetheless, measurements on grain sorghum of the CMSXS 769 are compared in Figure 16 to a curve plotted from dielectric data obtained by Nelson (1965) the only source to the authors' knowledge to have previously investigated dielectric data on grain sorghum. It's seen that the values of permittivity reported by Nelson (1965) on grain sorghum variety Martin at 12.5% w.b. moisture and 24°C agree quite well with the results for grain sorghum

CMSXS 769 at 12.8% w.b. moisture and 22 ℃. The type of variation of the dielectric parameters of grain sorghum with frequency, moisture content, and bulk density is very similar to published data on other agricultural commodities.

3.4 Uncertainties in relative permittivity and loss factor values

In the present work, as stated elsewhere (Trabelsi et al., 1998), potential errors in reference methods for determining grain moisture content and bulk density were not considered for the purpose of evaluating measurement errors. Therefore, the error analysis focused on calculated measurement uncertainties with the HP model 4285A Precision LCR meter while measuring C_p and G values, and consequently the associated accuracy in the derivation of ε' and ε'' through Equations (1) and (2). Error ranges in the relative permittivity values as they vary with frequency for samples of CMSXS 769 sorghum hybrid at 7.3% and 20.1% w.b moisture, with an average bulk density of (749 ± 4) kg/m^3, at (22 ± 1) ℃, are shown graphically in Figure 17. Errors in ε' values for samples of the other three hybrids, measured at the same conditions stated previously, were also within the range (±0.1% to ± 1.0%) shown in Figure 17. Uncertainties in ε'' values were within.

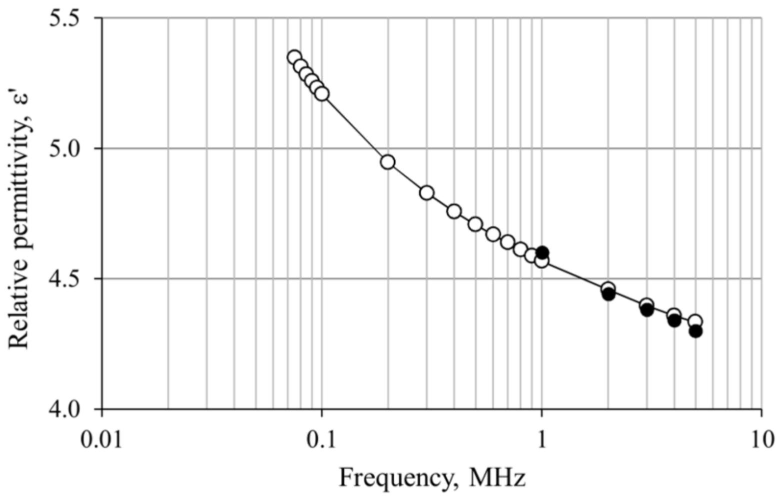

Figure 16 Comparison of the variation of permittivity with frequency as reported by Nelson (1965) (●) for Martin grain sorghum at 12.5% w.b. moisture, loose fill bulk density, and 24°C, with the results reported in the present work for the CMSXS 769 (○) at 12.8% w.b. moisture, 754 kg/m^3, 22°C and 62% relative humidity

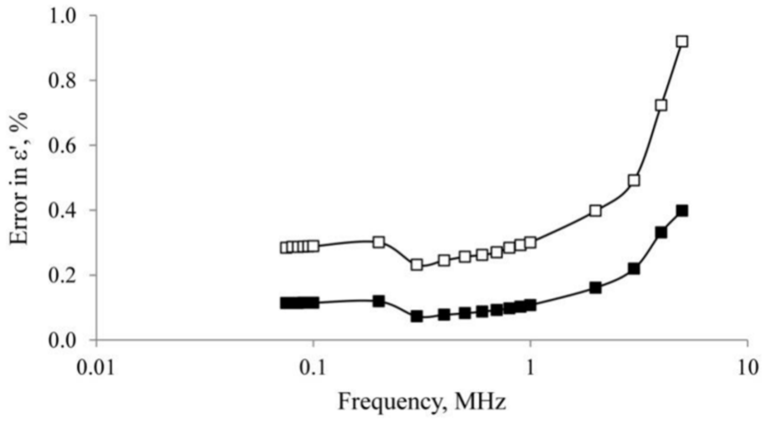

Figure 17 Error ranges (±) in the relative permittivity values as they vary with frequency for samples of CMSXS 769 sorghum hybrid at 7.3% w.b. (■) and 20.1% (□) w.b. moisture, with an average bulk density of 749 ± 4 kg/m^3, at 22°C ± 1 ℃

the range ±0.8% to ±12.0%. As errors related to scattering and other interfering factors such as the physical properties of each sample and instrument drift were not taken into account, the calculated error ranges presented here may be underestimated (Trabelsi, 2006). For comparison purposes, Stuchly et al. (1987) reported uncertainties below ±3% in ε', and ±1% in ε'', during radiofrequency dielectric measurements of biological tissues employing a network analyzer. Detailed measurement error analyses are not frequently reported in literature even when ε' and ε'', or other dielectric properties, are used as independent variables to estimate grain and seed moisture content or bulk density employing dielectric models (McKeown et al., 2012; Trabelsi et al., 2013).

4 Conclusions

Measurements of the dielectric properties of grain sorghum revealed that its permittivity was a function of grain moisture content, bulk density, hybrid, and frequency of the applied electric field. The value of relative permittivity ε', at given moisture contents and for similar values of bulk density, decreased regularly with increasing frequency. The dependence of the loss factor ε'' upon frequency was less regular than that of permittivity, and appeared either as upward or downward facing parabolic curves (depending on moisture) on a semi log plot. Relative permittivity increased with moisture content at every frequency where measurements were taken. The regression of moisture content on ε' and ε'' yielded cubic models with coefficients of determination very close to unity. The changes in permittivity and loss factor as a result of changes in moisture content were greater at lower rather than at higher frequencies. A region of possible dielectric dispersion was noticed in the moisture content range from 13% to 15% w.b. Straight lines were the best fit regression models representing the variation of ε' and ε'' on bulk density, with increasing slopes as moisture increases. Hybrid also had an effect on the dielectric parameters, with small-grain sorghum hybrids producing lower values of both ε' and ε'' as compared to large-grain hybrids.

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