A New Approach to Estimating Moisture Contents of Peanut Kernels through Microwaves Dielectric Measurements: A Comparative Study

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Abstract:
In the present paper we attempt at finding the moisture dependence of the relative permittivity and dielectric loss factor of Peanut kernel samples at 2.45 GHz to give quadratic and cubic models for the variation of the two dielectric properties with (i) decimal moisture content (m) (ii) moisture density (product of decimal moisture content and bulk density of the sample, m_d) and (iii) moisture specific volume (ratio of decimal moisture content to bulk density, m_v). The last parameter has been introduced by us in order to remove or minimize the irregularities in the variation of dielectric loss factor. Results and the plots for such variations, derived from seven formulae for the effective dielectric function of random media, are presented. On their bases, it is shown that the moisture content of a given sample could instantly be estimated for a given set of values for the two dielectric properties and that the technique may be assumed to be applicable almost over the entire range of moisture contents, without the aid of any reference data points. A better performance of our models compared with those of Bolder-Sanders-Simunovic (BSSM) is reported.

Keywords: Permittivity, Dielectric loss factor, Agricultural Products, Microwave frequency, Nonlinear regression, Peanuts.

PACS Nos: 77.22.d; 77.84.Lf; 78.70Gq; 81.40Tv.

1. INTRODUCTION
The use of electrical properties of grains for moisture measurement has been the most prominent agricultural application for dielectric properties data. The dielectric properties offer a potential means in making devices for sensing the moisture content of individual grain kernels, which help in preventing the spoilage of large blended lots stored in elevators, ships or mills[1-2]. Several efforts to model the dielectric properties of grains have been made [3-4]. The purpose of the present paper is to consider a more general approach towards modeling the dielectric properties of samples of peanut (Arachis hypogaea L), using the data for them at a fixed frequency of 2.45 GHz at 24°C, to present empirical expressions which allow predictions of permittivity and loss factor. The electrical properties of grains are influenced by ionic conductivities and bound-water relaxations. The result of measured values is then a complicated function of the amount of water in the grain. However, all these effects disappear almost completely at higher microwave frequencies. Thus, microwaves offer a nondestructive, sensitive and feasible method for determining the water content in grains.

The proposed models are:-

(Quadratic model)

\[ \varepsilon' = a \begin{pmatrix} m_d \end{pmatrix}^2 + b \begin{pmatrix} m_d \end{pmatrix} + K_1 \]

\[ \varepsilon'' = c \begin{pmatrix} m_d \end{pmatrix}^2 + d \begin{pmatrix} m_d \end{pmatrix} + K_2 \]

1(a) 1(b)

2. EXPERIMENTAL DATA: Data for measured values of bulk density, decimal moisture content (m) and dielectric constant were taken from the Table 5[5]. For deriving the values of bulk density p_b, kernel densities p_k and hence the volume fractions (p_b/p_k) of the material in the mixture, the tables 1 and 2, which give the values of bulk(in-shell) and kernel(shelled) densities, of the same paper[5] were used.

3. MODEL DEVELOPMENT AND EVALUATION OF CONSTANTS
Based on observations of evolved almost linear plots obtained for the dependence of relative permittivity of grains and cereals with moisture content, especially in the microwave range, it was proposed to give quadratic as well as cubic models for such variations. On similar lines of the works of Noh and Nelson[6-7] on rice samples, the second and a new term, called moisture density (product of decimal moisture content and bulk density), was also used. The third and the new term, called moisture specific volume (ratio of decimal moisture content to bulk density, m_v), in addition to m and m_d was also proposed to be incorporated in the composite model proposed in the present study.
\[ (\text{Cubic model}) \quad \varepsilon' = a \left( \frac{m}{m_v} \right)^3 + b \left( \frac{m}{m_v} \right)^2 + c \left( \frac{m}{m_v} \right) + K_1 \quad 2(a) \]

\[ \varepsilon = d \left( \frac{m}{m_v} \right)^3 + e \left( \frac{m}{m_v} \right)^2 + f \left( \frac{m}{m_v} \right) + K_2 \quad 2(b) \]

The values of the constants \( K_1 \) and \( K_2 \), which are relative permittivity’s and loss factor at \( M=0 \), respectively, where taken using the interpolation of almost linear plots of relative permittivity’s and loss factor as function of moisture contents as shown in Fig. 5[5]. The results have been presented in Table 1 and the evaluated constants are listed in Table 2. Of the present work. In order to extend the applicability of the present models to grain kernels, the values of relative permittivity of the moist grain samples, (supposed to be an air-particle binary mixture), were proposed to be converted to those of solid materials (particles) with the help of eight dielectric mixture equations [8–14].

**Brief Introduction of the Dielectric Mixture Equations Used**

(i) Rother–Lichtenecker formula or the logarithmic law of mixing for Chaotic mixture[ 8]

\[ \ln \varepsilon_r = \sum_{i=1}^{n} f_i \ln \varepsilon_i \quad [3a] \]

(for n-component mixture)

Thus, for an air-particle binary mixture

\[ \ln \varepsilon_r = f_1 \ln \varepsilon_1 + f_2 \ln \varepsilon_2 \quad [3b] \]

where

\( \varepsilon_r = \) permittivity of mixture
\( f_1 = \) volume fraction of air
\( \varepsilon_1 = \) permittivity of air \( = 1 \) \( \Rightarrow \ln \varepsilon_1 = 0 \)
\( f_2 = \) volume fraction of the particles,
with \( f_1+f_2 = 1 \), and
\( \varepsilon_2 = \) permittivity of the particulate materials.

Also, \( \varepsilon_2 = \exp \left[ \frac{1}{f_1} \ln \varepsilon_r \right] \quad [3c] \)

(ii) Taylor’s formula for random angular distribution of needle (9)

\[ 3 \varepsilon_r \left( \frac{\varepsilon_r - \varepsilon_H}{f} \right) = \left( \varepsilon_I - \varepsilon_H \right) \left( 2\varepsilon_I + \varepsilon_r \right) \quad [4a] \]

where

\( \varepsilon_i = \) permittivity of the inclusion
\( = \varepsilon_2 \) (for the present case)
\( \varepsilon_H = \) permittivity of the host (air) \( = 1 \)

The above expressions finally give:

\[ \varepsilon_2 = 0.25 \left\{ 2 + \frac{3}{f} (\varepsilon_r - 1) - \varepsilon_r \right\} + \left[ \left\{ 2 + \frac{3}{f} (\varepsilon_r - 1) - \varepsilon_r \right\}^2 + 8\varepsilon_r \right]^{1/2} \quad [4b] \]

(Taking only the positive root of the quadratic equation which the relation yielded)

(iii) Taylor’s formula for random angular distribution of disks, Taylor (9)

\[ \frac{3(\varepsilon_r - \varepsilon_H)(\varepsilon_I + \varepsilon_r)}{f} = (\varepsilon_I - \varepsilon_H)(5\varepsilon_r + \varepsilon_I) \quad [5a] \]

On similar pattern as above, one gets
As referred to earlier in the text, Taylor proposed a theory of elliptical inclusions of another dielectric material, which could be explained to include the case of lossy media in this case. The host medium is supposed to contain homogeneous random concentration of particles of the material with the condition that the field in the vicinity of the ellipsoid can be regarded as uniform and that \( l \ll \lambda \), where \( l \) is the large dimension of the ellipsoid and \( \lambda \) is the wavelength of the wave. Also, the average field approximations are valid only for \( f^2 \ll 1 \).

(iv) Lewin's formula (10)
Lewin proposed a formula for the computation of permittivity and permeability of mixture consisting of a homogeneous material in which spherical particles were embedded. The formula is given as:

\[
\frac{\varepsilon_r - \varepsilon_H}{\varepsilon_H} = 3f(\varepsilon_I - \varepsilon_H)(\varepsilon_H(1 + 2f) + \varepsilon_I(1 - f))^{-1}
\]

which in the present case simplifies to

\[
\varepsilon_2 = \left[ \varepsilon_r \left( 1 + 2f \right) - \left( 1 - f \right) \right] \left[ \left( 1 + 2f \right) - \varepsilon_r \left( 1 - f \right) \right]^{-1}
\]

Thus the upper limit to the usefulness of the above formula should be \( f \leq \frac{\pi}{6} \). However, it has been reported that higher values of \( f \) yielded acceptable results with the equation. Here the particles were supposed to be arranged in a cubic lattice spread in semi-infinite region, The relation has been reported to be valid at high frequency and hence it was supposed to be appropriate for the microwave frequency region of measurement of permittivity.

(v) Sillars formula (11)

\[
\varepsilon_r = \frac{\varepsilon_H \left[ \varepsilon_H + D(1 - f) + f \right]}{\varepsilon_H + D(1 - f) \times (\varepsilon_I - \varepsilon_H)}
\]

where \( D \) = depolarization factor, depending on the shape of the particles.

For the present case, the formula reduced to (taking \( \varepsilon_H = 1 \) and \( \varepsilon_I = \varepsilon_2 \)):

\[
\varepsilon_r = \frac{[1 + \{D(1 - f) + f\} \times (\varepsilon_r - 1)]}{[1 + D(1 - f) \times (\varepsilon_r - 1)]}
\]

\[
\Rightarrow \varepsilon_2 = \frac{(\varepsilon_r - 1)}{f - D(1 - f) \times (\varepsilon_r - 1)} + 1
\]

where \( D = 0.2 \)
Surprisingly enough, the data gave the best fit for the value of \( D = 0.2 \), as derived for rutile particles, suggesting that the shape of the particles were the same in both the cases. Otherwise, other values of \( D \) were to be tried for best fit.

(vi) Sadiku's formula[12]

\[
\frac{(\varepsilon_r - 1)}{(\varepsilon_r + u)} = \frac{f(\varepsilon_I - 1)}{(\varepsilon_2 + u)} + \frac{(1 - f)(\varepsilon_H - 1)}{(\varepsilon_H + u)}
\]

Where, \( u \) is the form number depending on the shape of the particles. The value of \( u = 5 \) for snow or ice (Sadiku, 1985) gave the best fit, as \( D = 0.2 \) for rutile in the previous study (Prasad and Sharma) equation 3.5. It also suggested a possible relationship, such as \( D = 1/u \). It was proposed to take \( u = 5 \) in this case to examine the goodness of the fit. For the present case, \( \varepsilon_4 = 1 \) and \( \varepsilon_1 = \varepsilon_2 \) as before, and we find that:

\[
(\varepsilon_r - 1)/(\varepsilon_r + u) = f(\varepsilon_2 - 1)/(\varepsilon_2 + u)
\]

which finally gives:

\[
\varepsilon_2 + 2 = 3[\varepsilon_r(1 + f) + (5f - 1)]/[(1 + 5f)\varepsilon_r(1 - f)]
\]
The equation finally gives:

\[
\varepsilon_r = \frac{\varepsilon_H \left[ (1 + 2f)\varepsilon_r + 2\varepsilon_H (1 - f) \right]}{\varepsilon_1 (1 - f) + (2 + f)\varepsilon_H}
\]

\[
\varepsilon_2 = \frac{((2 + f)\varepsilon_r - 2(1 - f))}{1 + 2f - \varepsilon_r (1 - f)}
\]

In the above formula, particulate material has been taken as the first component and air as the second one, under the limiting case of small concentration of the component A in the binary system AB – opposed to those taken in other formulae.

\[(vii)\] Formula obtained from Effective Medium Theory (13)

\[
\varepsilon_{\text{eff}} = \varepsilon_1 \left[ 1 + \frac{3f_2(\varepsilon_2 - \varepsilon_1)}{\varepsilon_2(2 + f_2) + \varepsilon_2(1 - f_2)} \right]
\]

For the present case

\[
\varepsilon_{\text{eff}} = \varepsilon_r; \varepsilon_i = \varepsilon_H = 1; f_2 = f \text{ (say)}
\]

The equation finally gives:

\[
\varepsilon_r = 1 + \frac{3f(\varepsilon_2 - 1)}{((2 + f) + \varepsilon_2(1 - f))}
\]

The above expression has been claimed by the investigator (Skipetrov, 1999) to be an original one for the effective dielectric function of dilute suspension of spherical beads of diameter d << λ. Further, it has been claimed that the above formula is expected to be more appropriate for the interpretation of the experiments and behaviour at higher volume fractions. Thus, it is apparent that in all the above equations, except the last one, air has been taken as the first component and the particulate material as the second one.

4. METHODOLOGY

Using any measured value of \(\varepsilon_i\), the corresponding value of volume fraction of the particle, \(f_2\), the value of the permittivity of the particles, \(\varepsilon_2\) (=\(\varepsilon_{\text{eff}}\), say) was calculated choosing any of the eight equations, say the first one. The constants of the first set of equations concerning relative permittivity versus m for the quadratic or the cubic model, as the case may be, were used to compute the value of m, \(m_2\), (say). Using these values of m and the constants evaluated for the second set of equations (concerning loss factor versus moisture content, say), the value of loss factor of the particles (kernels), \(\varepsilon_2\) were calculated. Thus one gets the values of \(\varepsilon_2\) and \(\varepsilon_2\) for a given computed value of m (say). The same process was repeated for different values of volume fractions of a given sample. A similar process was adopted by taking another dielectric mixture equation one by one, to get the data points. The same process was repeated for computation of \(\varepsilon_2\) and \(\varepsilon_2\) as functions of \(m_\text{a}\) and \(m_\text{b}\) for both types of the proposed models. It was expected to achieve the estimates of \(\varepsilon_2\) and \(\varepsilon_2\) of peanut kernel as functions \(m_\text{a}\), \(m_\text{b}\) and \(m_\text{c}\).

Table 1. Data of measured values of relative permittivity and loss factor of Peanut at 23°C and 2.45GHz at different bulk densities and moisture contents.

<table>
<thead>
<tr>
<th>Moisture content in % (wet basis)</th>
<th>Bulk density in g/cm³</th>
<th>Kernel density in g/cm³</th>
<th>Permittivity (\varepsilon'_r)</th>
<th>Loss factor (\varepsilon''_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.25</td>
<td>0.332</td>
<td>0.628</td>
<td>4.67</td>
<td>0.95</td>
</tr>
<tr>
<td>18.70</td>
<td>0.3386</td>
<td>0.6546</td>
<td>5.42</td>
<td>1.26</td>
</tr>
<tr>
<td>24.81</td>
<td>0.3386</td>
<td>0.7153</td>
<td>8.9</td>
<td>2.5</td>
</tr>
<tr>
<td>28.06</td>
<td>0.3843</td>
<td>0.7513</td>
<td>7.77</td>
<td>2.12</td>
</tr>
</tbody>
</table>

Table 2. Evaluated parameters and constants for models concerning relative permittivity and loss factor, measured at 23°C and 2.45 GHz, for shelled peanut kernels.

<table>
<thead>
<tr>
<th>Table (A₁)</th>
<th>Present Quadratic Model</th>
<th>Present Cubic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolder- Sanders -Simunovic(BSS) quadratic model for relative permittivity corresponding to different moisture levels</td>
<td>(A_2=8.384E-6; A_1=5.930E-4; r^2=0.949; M=18%; \rho_a=0.628 \text{ g cm}^{-3}; \rho_b=0.332 \text{ g cm}^{-3})</td>
<td>(a_2 = 26.3517)</td>
</tr>
<tr>
<td>(A_2=1.327E-5; A_1=1.811E-3; r^2=0.996; M=23%; \rho_a=0.654 \text{ g cm}^{-3}; \rho_b=0.3386 \text{ g cm}^{-3})</td>
<td>(a_3 = -1784.3139)</td>
<td>(b_2 = 17.4833)</td>
</tr>
<tr>
<td>(K_1 = 1.6044)</td>
<td>(b_3 = 817.1461)</td>
<td>(c_1 = -65.9110)</td>
</tr>
<tr>
<td>(K_1 = 1.6044)</td>
<td>(c_2 = 5.930E-4)</td>
<td>(c_3 = -5.930E-4)</td>
</tr>
</tbody>
</table>
(B1) Models for relative permittivity as function of moisture density, \( m_d \):

\[
B_2 = 3.22 \times 10^{-6}; \ B_1 = -4.96 \times 10^{-4}; \ r^2 = 0.988; \ M = 18\%; \ \rho_k = 0.628 \text{ g cm}^{-3}; \ \rho_b = 0.332 \text{ g cm}^{-3}
\]

\[
B_2 = 5.201 \times 10^{-6}; \ B_1 = -1.475 \times 10^{-3}; \ r^2 = 0.986; \ M = 23\%; \ \rho_k = 0.654 \text{ g cm}^{-3}; \ \rho_b = 0.3386 \text{ g cm}^{-3}
\]

\[
B_2 = 4.677 \times 10^{-6}; \ B_1 = 1.840 \times 10^{-4}; \ r^2 = 0.930; \ M = 33\%; \ \rho_k = 0.654 \text{ g cm}^{-3}; \ \rho_b = 0.3386 \text{ g cm}^{-3}
\]

\[
B_2 = 1.251 \times 10^{-5}; \ B_1 = -6.55 \times 10^{-3}; \ r^2 = 0.884; \ M = 39\%; \ \rho_k = 0.7513 \text{ g cm}^{-3}; \ \rho_b = 0.3843 \text{ g cm}^{-3}
\]

(B2) Models for loss factor as function of moisture density, \( m_d \):

\[
c_2 = 5.0952; \ d_3 = -672.2526
\]

\[
d_3 = 4.1318; \ e_3 = 313.0325
\]

\[
K_2 = 0.06808; \ f_3 = 27.2876
\]

\[
K_2 = 0.06808
\]

(C1) Models for relative permittivity as function of moisture specific volume, \( m_v \):

\[
a_2 = 20.8227; \ b_2 = 37.1967; \ K_1 = 1.6044
\]

\[
a_3 = 4406.1947; \ b_3 = 1381.7955; \ c_3 = 0.066236; \ K_1 = 1.6044
\]

(C2) Models for loss factor as function of moisture specific volume, \( m_v \):

\[
c_2 = 3.2478; \ d_2 = 10.3617; \ K_2 = 0.06808
\]

\[
d_2 = -0.9029; \ e_2 = 205.7482; \ f_2 = 29.2466; \ K_2 = 0.06808
\]

\[
c_2 = 19.2152; \ d_2 = -298.9346; \ K_2 = 0.06808
\]

\[
e_2 = 298.9346; \ f_2 = 29.2466; \ K_2 = 0.06808
\]

Table 3(A)

<table>
<thead>
<tr>
<th>Bolder-Sanders-Simunovic (BSS) Model for relative permittivity</th>
<th>Prasad - Singh Model (PSM) for relative permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted values</td>
<td>average ( r^2/)average %error</td>
</tr>
<tr>
<td>4.68</td>
<td>0.956</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

Table 3(B)

<table>
<thead>
<tr>
<th>Bolder-Sanders-Simunovic (BSS) Model for loss factor</th>
<th>Prasad - Singh Model (PSM) for loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted values</td>
<td>average ( r^2/)average %error</td>
</tr>
<tr>
<td>0.96</td>
<td>0.947</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

Table 3. (A) & (B): Comparative performances of different models for the variation of relative permittivity and loss factor with moisture content of peanut at 23 °C and 2.45 GHz.
However, the constants for in-shell and shelled samples for the same moisture levels were different. The ratio of density of in-shell i.e. peanut pods and shelled grain sample at the fixed moisture content was taken as the volume fraction of the inclusion material in the sample, as the first. The data of measured values of relative permittivity and dielectric loss factor of peanut bulk samples at four different moisture contents ranging from 15.25% to 28.06% (wet basis) and bulk and kernel densities corresponding to 23°C and 2.45 GHz as taken from the literature [5], are presented in Table 1. Table 2 presents the constants and model parameters for the present quadratic and cubic models relating relative permittivity and dielectric loss factor to $m$, $m_d$, and $m_v$ evaluated with the help of least-squares-fit method for non-linear regression analysis. Table 3(A) presents the quantitative comparative performances of the moisture-dependent models (BSSM) and similar models for relative permittivity proposed in the present study. The table 3(B) presents the comparative performance for the same models for loss factor. The tables also present the average percentage errors of prediction for the different models with respect to the measured values of two dielectric properties ($\varepsilon'$ and $\varepsilon''$) along with the coefficients of determination ($r^2$).

5. RESULTS AND DISCUSSION

For different fixed moisture contents ranging from 18% to 39% (wet basis) the density-dependent quadratic models for the variation of relative permittivity ($\varepsilon'$) and loss factor ($\varepsilon''$) for in-shell as well as for ground shelled peanuts were;
The present models have shown their acceptability in predicting the moisture dependent complex permittivity of rice kernels[15]. The models fittings are excellent and the models have shown encouraging results in other grains and cereals, but the evolved disappointing results in the present study may be attributed to the following:

- The assumption of the seed to be an air-particle binary-phase mixture and not a ternary (air-water(oil)-particle)may have led to erroneous results for density and moisture measurements;
- In view of the above, the first-order approximation used in computation of volume fraction of particles for deriving the kernel permittivities at different moisture levels and through the different mixture equations, used in the present models, may have led to the poor fits for them in compression with others: Treating the first-order approximate complex refractive index equation and ‘Lifshitz-Looyenga equation’[2] as the accurate mixture
- equations for random dielectric media, equations [6], [7], [8], and [9] might have led to irregular trends of moisture-dependent variation for both the dielectric properties. The variation are shown in fig.5 [5]. In no way these variations could be modeled, whereas the present quadratic and cubic models present regular types of moisture-dependent complex permittivity variations. Thus, there is still a scope for further investigation in the form of comparison of the present models with other well established models, if any, for peanut as well as for other granular materials.

6. REFERENCES