Microwave density – independent permittivity functions as soybean seeds' moisture calibrators: A new approach

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Abstract: The present work makes use of data for real part of microwave complex permittivity as function of moisture content measured at 2.45 GHz and 24℃, as extracted from the literature. The data were individually converted to those for solid materials using seven independent mixture equations for effective permittivity of random media. Moisture dependent quadratic models, as developed by the present group, were used to evaluate the dielectric loss factor of soybean seeds. Using these data, a number of density – independent permittivity functions were evaluated and plotted as a function of moisture content of the samples. Second and third order polynomial and first order exponential growth type of curve fittings with these data have been tried and their performances are reported. Coefficients of determination (r^2) approaching unity (≈0.989 – 0.999) and very small Standard Deviation (SD) up to 3.45×10^{-4} for these models possess good acceptability. The regularity in the nature of these variations revealed the usefulness of these densities – independent permittivity functions as indicators/calibrators of moisture content of soybean seeds. Keeping in view the fact that moisture content of grains and seeds is an important factor determining quality and affecting the storage, transportation, and milling of grains and seeds, the work has the potentiality of its practical applications.

Keywords: microwave complex permittivity, density-independent permittivity functions, soybean, Dielectric Mixture equations, moisture meters, least–squares fit analysis

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1 Introduction

Dielectric properties of cereal grains are highly correlated with moisture content (Nelson, 1981 & 1991). Therefore, electrical moisture meters have been developed for rapidly sensing grain moisture content (Nelson, 1977 & 2006) in order to ascertain their quality appropriate for storage, transportation, and milling. Because the dielectric properties of hygroscopic granular materials depend on temperature and bulk density of the materials at the time of measurement as well as the moisture content, moisture calibrations must take into account corrections for difference in bulk density and temperature. These corrections have, to a great extent, been incorporated into the design of most modern moisture meters, which determine the grain moisture content from measurements on static samples. Modern agriculture requires moisture sensing on moving grain for continuous monitoring of moisture content on harvesting, conveying and processing equipment (Nelson, 2000 & 2006). Grain temperature measurement can be accomplished relatively easily and inexpensively in a moisture meter, but fluctuations in the bulk density of moving granular materials are difficult to handle in such instruments because the density of a granular material depends upon the particle shape and size, temperature, moisture content, surface structure, and condition. Thus, providing a constant material density during continuous moisture content measurement under industrial conditions is a difficult task. Various ways of limiting variations in density of grains and seeds have been proposed by different researchers and the results derived from these suggested measures have been tested, but the ultimate conclusion from those studies was that the only reliable

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solution to the problem is the use of some density – independent function e.g., a relationship between electrical properties of material and its moisture content. For measurements at microwave frequencies, moisture calibration functions of measured parameters or the dielectric properties of the grains have been developed (Kraszewski and Kulinski, 1976; Jacobson, Mayer and Schrage, 1980; Mayer and Schilz, 1980) that are relatively independent of bulk density of the granular material.

Considerable study has been devoted to the development of density – independent permittivity functions that would eliminate the need for weighing, and thus, permit on-line measurement of moisture content (Kraszewski and Kulinski, 1976; Mayer and Schilz, 1980, 1981; Powell et al., 1988; Kraszewski and Nelson, 1991, 1992; Mclendon et al., 1993; Trabelsi, Kraszewski and Nelson, 1997, 1998, 2001a and 2001b) in which different combinations of the components of material permittivity have been proposed.

Measurements of attenuation (A) and phase shift (φ) for grain, specially in the range of microwave frequencies, have shown that both are almost linear with moisture content (Kraszewski, 1988) and a simple ratio of the two measured quantities (attenuation and phase shift), in most of the cases both normalized to layer thickness and density of the sample, was to a great extent, at least in the range of practical interest, independent of material density (Kent and Kress-Rogers, 1986; Kress-Rogers and Kent, 1987; Kraszewski and Nelson ,1991).

A survey of the aforementioned and other similar literatures revealed that moisture-dependent variation of the different density – independent permittivity functions showed more or less different trends in the sense that some showed increasing while some others showed decreasing trend of variation with increasing moisture content. Therefore, the development of reliable mathematical models that can accurately describe and predict the process of moisture-dependent variation of density-independent permittivity functions of moist grains and seeds would be extremely helpful in understanding the process as well as in optimizing the design of moisture meters. The purpose of the present study is to modify the different chosen density-independent permittivity functions or the ratio of attenuation to phase shift or its inverse in such a way as to get almost similar increasing trend of variation with the increase of moisture content, at least qualitatively, in order to evaluate their comparative performances in providing accurate calibration functions for granular materials like grains and seeds almost over the entire range of material density in bulk to that in particulate form.

2 Mathematical analysis

2.1 Chosen forms of density-independent permittivity functions with their brief introduction

First form is simply the inverse of the function chosen by Lawrence and Nelson (Lawrence and Nelson, 1993) and reads as:

$$\psi_1 = (\varepsilon''/(\varepsilon'-1)) \tag{1}$$

Where, ε' and ε'', respectively, represent the real and imaginary parts of complex permittivity.

Second form has also been taken from the same literature (Lawrence & Nelson 1993) and it reads as:

$$\psi_2 = ((\varepsilon'')^{1/2}/((\varepsilon')^{1/3}-1)) \tag{2}$$

Where 'epsilon' terms have their usual meanings as before.

Two forms of the third function, finding their different places in the literature (Kraszewski, 1988; Trabelsi, Kraszewski and Nelson, 1998), were found to be exactly identical. They are given as:

$$\psi_{3a} = \frac{1}{13.193}.\frac{\varepsilon''}{\varepsilon'-1}.\frac{(\sqrt{\varepsilon'}+1)}{\sqrt{\varepsilon'}} \tag{3a}$$

and

$$\psi_{3b} = c\left(\frac{\varepsilon''}{\varepsilon'-\sqrt{\varepsilon'}}\right) \tag{3b}$$

Where, c = 0.0758.

For plane wave propagation through low loss dielectric materials, the ratio of attenuation to phase shift can be expressed as the fourth density – independent permittivity function (Kent and Kress-Rogers, 1986; Kress-Rogers and Kent, 1987) which is of the form:

$$\psi_4 = \frac{A}{\Phi} = \frac{\varepsilon''}{\varepsilon'-1}\left(\frac{\sqrt{\varepsilon'+1}}{2\sqrt{\varepsilon'}}\right) \tag{4}$$

A new density-independent permittivity function for moisture calibration in microwave measurements has been reported in the literature (Nelson, Kraszewski and Trabelsi, 2000; Trabelsi, Kraszewski and Nelson, 2001a and 2001b) and the same has been used as the fifth density-independent permittivity function in the present study. It is read as:

$$\psi_5 = \sqrt{\frac{\varepsilon''}{\varepsilon'(a_f.\varepsilon' - \varepsilon'')}} \tag{5}$$

Where, a_f is the slope of the ε'/ρ vs. ε''/ρ plot at a given frequency. Instead of taking the value of a_f for soybean samples from the literature (Nelson, Kraszewski and Trabelsi, 2000), its value was found out from density-dependent complex permittivity data given in Table 1 of the present study. It was found to be equal to 0.34528 corresponding to the experimental values of complex permittivity at 2.45 GHz. and 24℃ (as obtained from the almost linear plot shown in Figure 5a, whereas the corresponding value at 9.4 GHz, as given in the aforementioned literature (Nelson, Kraszewski and Trabelsi, 2000), is equal to 0.619.

The sixth density-independent permittivity function chosen for the present study is of the form (Kraszewski, 1991):

$$\psi_6 = \frac{29.3m - 1.936}{355.8m + 45.32} \tag{6}$$

Where, m = decimal moisture content (wet weight basis).

The evaluated parameters given in Eq. (6) correspond to hard red winter wheat, but it was asserted that it could be applied to other grains having even different shapes and compositions as well. It is with this view that the function with the same set of parameters were tried for the soybean samples and, surprisingly enough, all the experimental and computed data points fell on regular type of curve with good quadratic fitting parameters. The details of the fitting characteristics will be discussed later.

2.2 Brief introduction to the dielectric mixture equations used (Prasad and Singh , 2007)

Rother-Lichtenecker equation for an n-component mixture:

$$\ln\varepsilon_r = \Sigma f_I \ln\varepsilon_I \tag{7a}$$

Thus for an air-particle binary mixture

$$\ln\varepsilon_r = f_1\ln\varepsilon_1 + f_2\ln\varepsilon_2 \tag{7b}$$

For an air-particle binary mixture, the equation reduces to:

$$\varepsilon_2 = \exp[1/f_2\ln\varepsilon_r] \tag{7c}$$

(In the subsequent equations, f is used instead of f_2 only for the sake of simplicity.)

Taylor equation for random angular distribution of needles:

$$3\varepsilon_r(\varepsilon_r - \varepsilon_H)/f = (\varepsilon_I - \varepsilon_H)(\varepsilon_I + \varepsilon_H) \tag{8a}$$

The above expression yields:

$$\varepsilon_2 = 0.25[\{2+3/f(\varepsilon_r - 1) - \varepsilon_r\} + [[\{2+3/f(\varepsilon_r - 1) - \varepsilon_r]^2 + 8\varepsilon_r]^{1/2}] \tag{8b}$$

Taylor equation for random angular distribution of disks:

$$[3(\varepsilon_r - \varepsilon_H)(\varepsilon_I + \varepsilon_r)]/f = (\varepsilon_I - \varepsilon_H)(5\varepsilon_r + \varepsilon_I) \tag{9a}$$

On substitutions and rearrangement:

$$\varepsilon_2 = 0.5[[(1-3/f) + (5-3/f)\varepsilon_r] + [\{(1-3/f) + (5-3/f)\varepsilon_r\}^2 + 4\{(3/f)\varepsilon_r^2 + (5-3/f)\varepsilon_r\}]^{1/2}] \tag{9b}$$

Lewin equation:

$$(\varepsilon_r - \varepsilon_H)/\varepsilon_H = 3f(\varepsilon_I - \varepsilon_H)/\{\varepsilon_H(1+2f) + \varepsilon_I(1-f)\} \tag{10a}$$

Which in the present case it simplifies to

$$\varepsilon_2 = [\varepsilon_r(1+2f) - (1-f)]/[(1+2f) - \varepsilon_r(1-f)] \tag{10b}$$

Sillars equation:

$$\varepsilon_r = \varepsilon_H[\varepsilon_H + D(1-f) + f][\varepsilon_I - \varepsilon_H]/[\varepsilon_H + D(1-f)(\varepsilon_I - \varepsilon_H)] \tag{11a}$$

Where, D is the depolarization factor depending on the shape of the particles. For the present case, Eq. (11a) reduces to

$$\varepsilon_r = [1 + \{D(1-f) + f\}(\varepsilon_r - 1)]/[1 + D(1-f)(\varepsilon_2 - 1)] \tag{11b}$$

$$\Rightarrow \varepsilon_2 = [\{\varepsilon_r - 1\}/[f - D(1-f)(\varepsilon_r - 1)\}] + 1 \tag{11c}$$

Where, D = 0.2.

Weiner equation:

$$\frac{(\varepsilon_r - 1)}{(\varepsilon_r + u)} = \frac{f(\varepsilon_I - 1)}{(\varepsilon_2 + u)} + \frac{(1-f)(\varepsilon_H - 1)}{(\varepsilon_H + u)} \tag{12a}$$

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 equation 11. It also suggested a possible relationship, such as D = 1/u. We propose to take u = 5 in this case to examine the goodness of the fit. For the present case, ε_H = 1 and $\varepsilon_I = \varepsilon_2$ as before, and we get

$$(\varepsilon_r - 1)/(\varepsilon_r + u) = f(\varepsilon_2 - 1)/(\varepsilon_2 + u) \quad (12b)$$

Which finally gives

$$\varepsilon_2 + 2 = 3[\varepsilon_r(1+f) + (5f-1)]/[(1+5f)\varepsilon_r(1-f)] \quad (12c)$$

Skipetrov equation:

$$\varepsilon_{eff} = \varepsilon_1[1 + \{3f_2(\varepsilon_2 - \varepsilon_I)\}/\{\varepsilon_I(2+f_2) + \varepsilon_2(1-f_2)\}] \quad (13a)$$

For the present case

$$\varepsilon_{eff} = \varepsilon_r; \quad \varepsilon_1 = \varepsilon_H = 1; \quad f_2 = f \text{ (say)}$$

The equation finally gives:

$$\varepsilon_r = 1 + [3f(\varepsilon_2 - 1)]/[(2+f) + \varepsilon_2(1-f)] \quad (13b)$$

Webmann equation for effective medium theory (EMT):

$$\varepsilon_H[(1+2f)\varepsilon_I + 2\varepsilon_H(1-f)]/[\varepsilon_I(1-f) + (2+f)\varepsilon_H] \quad (13c)$$

Unlike other cases, $\varepsilon_B = \varepsilon_H = 1$ and $\varepsilon_A = \varepsilon_2$, thus giving

$$\varepsilon_2 = [(2+f)\varepsilon_r - 2(1-f)]/[1 + 2f - \varepsilon_r(1-f)] \quad (13d)$$

3 Methodology, results and discussion

Using the experimental moisture – dependent complex permittivity data in the method of least-squares fit analysis for non-linear (quadratic) regression equations, the constants [(a,b) & (c,d)] in the two equations given below (Equations (14) and (15)) were evaluated. The equations are:

$$\varepsilon' = am^2 + bm + k_1 \quad (14)$$

$$\varepsilon'' = cm^2 + dm + k_2 \quad (15)$$

The values of the constants k_1 and k_2 (permittivity and dielectric loss factor values, respectively, corresponding to m = 0) were taken from the literature (Nelson, 1987; Nelson and You, 1987) using the interpolation of almost linear plots of relative permittivity and loss factor as function of moisture content. The evaluated constants are listed in Table 3. For a given evaluated real part of complex permittivity of particles (solids) and the constants a, b, k_1 as given in Table 3 are put in Equation (14) to get the computed value of 'm' which, when put along with the constants c, d, and k_2 from Table 3, in Equation (15) give the dielectric loss factor of particles corresponding to the computed value of 'm'. This process of evaluation of both parts of complex permittivity for particles, ε'_2 and ε''_2, respectively, was repeated using the other six independent mixture equations as detailed elsewhere (Prasad and Singh 2007). The same process was repeated for different experimental values of moisture content (as given in Table 1).

Table 1 Experimental data of relative permittivity and dielectric loss factor of soybeans (*Glycine max* (L.) merill) at 24℃ and 2.45 GHz. at different bulk densities and moisture contents

Moisture content /% wet weight basis	Bulk density /g • cm^{-3}	Seed density /g • cm^{-3}	Relative permittivity $\varepsilon'(\varepsilon_r)$	Loss factor $\varepsilon''(\varepsilon_r'')$
7.5	0.827	1.233	2.28	0.14
10.4	0.761	1.230	2.57	0.27
12.3	0.718	1.225	2.71	0.36
15.0	0.692	1.222	2.96	0.48

Table 2 Data of experimental as well as computed values of complex permittivity as function of decimal moisture content of soybean bulk and seed samples corresponding to 2.45 GHz and 24℃

Decimal Moisture Content/m	Relative permittivity (ε')	Loss factor (ε'')	Decimal Moisture Content/m	Relative permittivity (ε')	Loss factor (ε'')
Rother-Lichtenecker equation			Taylor equation for random angular distribution of needles		
0.1945	3.4153	0.7965	0.1624	3.0903	0.5722
0.2993	4.5946	1.7846	0.2353	3.8530	1.1347
0.3690	5.4809	2.6585	0.2775	4.3347	1.5468
0.4629	6.8025	4.1096	0.3328	5.0098	2.1830
Taylor equation for random angular distribution of disks			Lewin equation		
0.2432	3.9401	1.2070	0.1682	3.1477	0.6100
0.2679	4.2224	1.4475	0.3485	5.2112	2.3835
0.2725	4.2753	1.4947	0.4718	6.9353	4.2634
0.3027	4.6360	1.8232			
Sillars equation			Weiner equation		
0.1716	3.1814	0.6327	0.1665	3.1304	0.5988
0.2611	4.1440	1.3791	0.2506	4.0233	1.2768
0.3199	4.8478	2.0249	0.3042	4.6538	1.8404
0.4036	5.9511	3.1566	0.3794	5.6202	2.8038
Skipetrov equation					
0.1942	3.4122	0.7942			
0.3113	4.7416	1.9227			
0.3989	5.8854	3.0865			
0.5364	7.9392	5.4646			

Table 3 Model parameters for moisture-dependent permittivity variation for soybeans corresponding to measurement at 2.45 GHz and 24℃

Model	Parameters
Quadratic: As at Eq.(14) and (15)	a = 8.3295, b = 7.1430, c = 17.8190 d = 0.6296, k_1 = 1.71, k_2 = 0

Using the fifteen Equations (1) – (15) and Tables (1, 2 & 3), seven independent sets of real and imaginary parts of complex permittivity corresponding to the computed moisture constants were obtained. The detailed analysis made by the present group may be seen elsewhere (Prasad and Singh, 2007). Six independent sets of density-independent permittivity functions as deduced from the Equations (1) – (6) corresponding to the experimental as well as theoretical set of complex permittivity data were thus obtained and these data are shown graphically in Figures 1 through 6 in which six moisture–dependent density–independent microwave permittivity functions for soybean bulk and seed samples are shown.

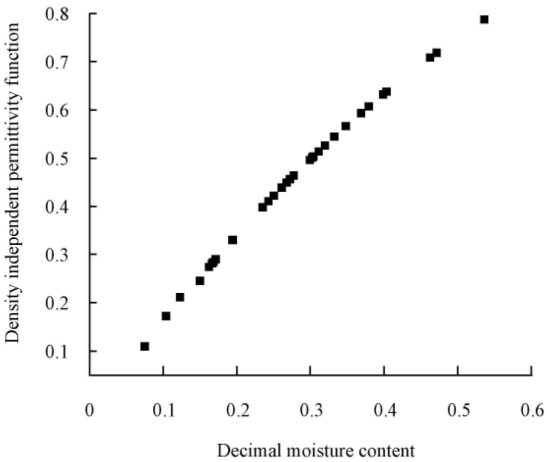

Figure 1 Dependence of first density independent permittivity function (psi 1) as a function of decimal moisture content (wet weight basis) of soybean bulk and seed samples

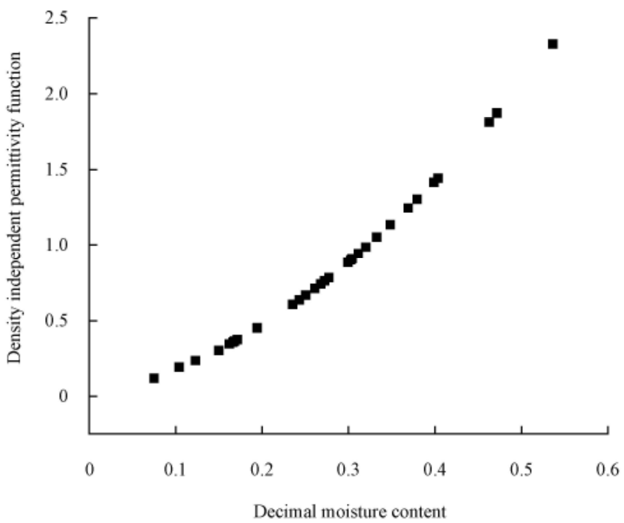

Figure 2 Dependence of second density independent permittivity function (psi 2) as a function of decimal moisture content (wet weight basis) of soybean bulk and seed samples

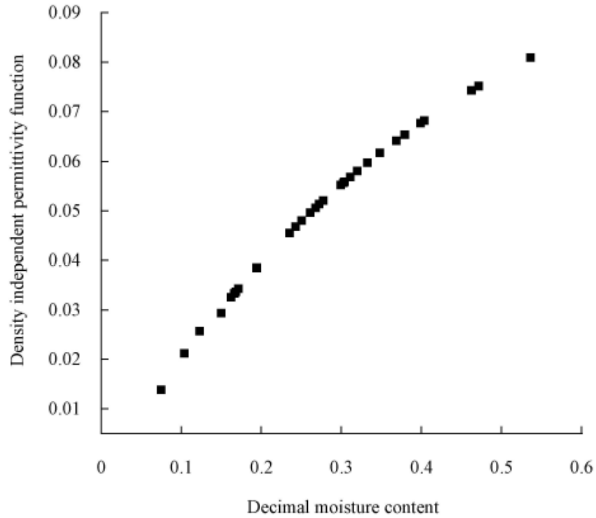

Figure 3 Dependence of third density independent permittivity function (psi 3) as a function of decimal moisture content (wet weight basis) of soybean bulk and seed samples

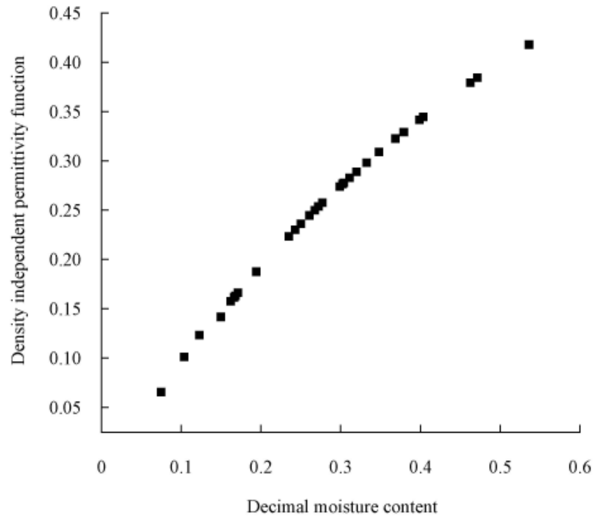

Figure 4 Dependence of fourth density independent permittivity function (psi 4) as a function of decimal moisture content (wet weight basis) of soybean bulk and seed samples

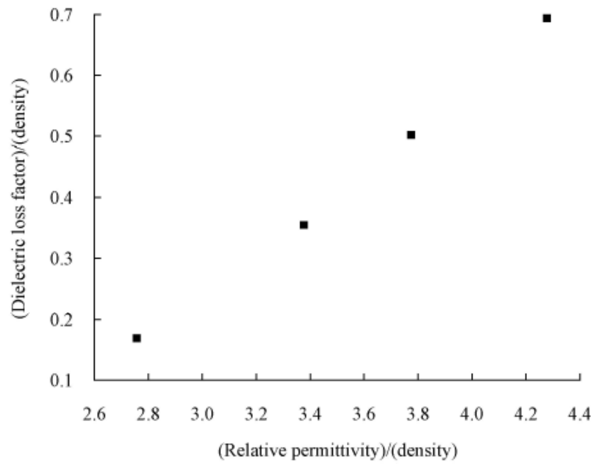

Figure 5a Dependance of (Dielectric loss factor)/(density) as a function of (Relative permittivity)/(density)corresponding to experimental complex permittivity data of soybeans at 2.45 GHz and 24℃

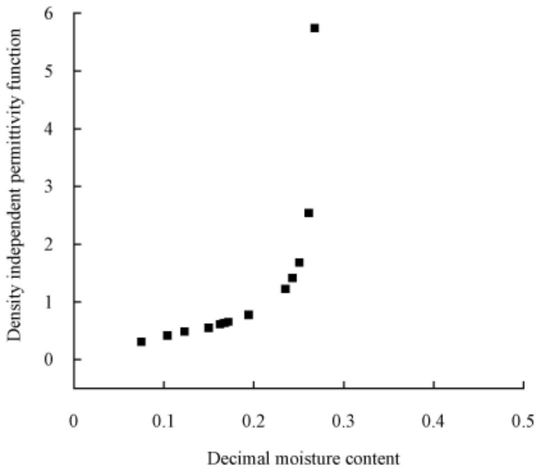

Figure 5b Dependence of fifth density independent permittivity function (psi 5) as a function of decimal moisture content (wet weight basis) of soybean bulk and seed samples

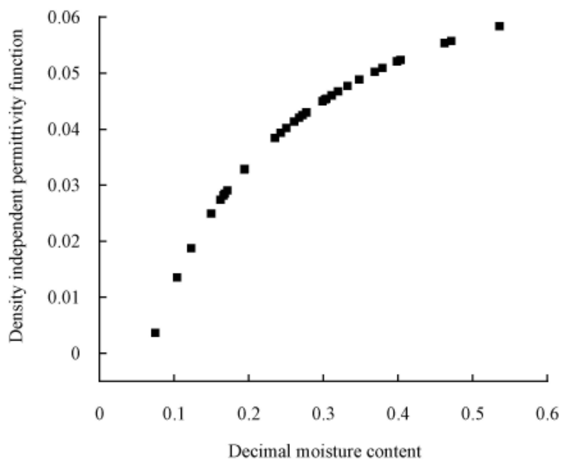

Figure 6 Dependence of sixth density independent permittivity function (psi 6) as a function of decimal moisture content (wet weight basis) of soybean bulk and seed samples

Moisture–dependent complex permittivity data for ground soybean samples corresponding to 2.45 GHz and 24℃, taken from the literature (Nelson 1987; Nelson and You, 1987), are given in Table 1 and the data for real part of permittivity converted to those for solid materials (particles) using seven independent mixture equations for effective permittivity of random media by putting the measured values of real part of permittivity and volume fraction of particles in them from Table 1, are presented in Table 2. Moisture – dependent density – independent microwave permittivity data were put to second order polynomial fittings in five of the six cases and only for the fifth function, third order polynomial and first order exponential growth types of fittings were tried. The numerical coefficients and fitting parameters for the given fits are listed in Table 4.

The goodness of fit of the models is determined from the values of coefficient of determination (r^2), standard deviation (*SD*), average fractional error of prediction (*p*). The number of data points chosen for the study is denoted by N. The r^2-values of the different models are in the range 0.990 – 0.999 for the second order polynomial fitting in almost all the cases except in the case of fifth density–independent permittivity function for which the second order polynomial provided rather poorer fitting ($r^2 \approx 0.73$). The third order polynomial provided a bit improved but not very satisfactory fit ($r^2 \approx 0.87$). The first order exponential growth also did not provide satisfactory fit in the sense that it provided a value of $r^2 \approx 0.82$ and that of chi-squared upon degrees of freedom ≈0.12. The SD value is the least ($\approx 3.4536\times10^{-4}$) and r^2–value is maximum (≈0.99958) for the third density-independent permittivity function.

Table 4 Model parameters and fitting parameters for polynomial and exponential growth type of regression equations for moisture-dependent variation of six density-independent permittivity functions for measured permittivity data of soybean samples corresponding to 24℃ and 2.45GHz

Functions/ Model	Constants (Model Parameters)			Fitting Parameters for the models			
	A	B_1	B_2	r^2	*SD*	*N*	*P*
Ψ_1/quadratic	–0.03938	2.10411	–1.05297	0.99983	0.00221	32	<0.0001
Ψ_2/quadratic	0.94374	4.97812	–4.57097	0.98944	0.02811	32	<0.0001
Ψ_3/quadratic	–0.00232	0.24038	–0.16118	0.99958	3.4536E-4	32	<0.0001
Ψ_4/quadratic	–0.0153	1.58561	–1.06319	0.99958	0.00228	32	<0.0001
Ψ_5/quadratic	1.61295	–14.19401	35.86509	0.73462	0.43122	32	<0.0001
Ψ_5/cubic	–1.86966	3.3674 B_3=133.17226	–158.69085	0.87192	0.30507	32	<0.0001
Ψ_5/exponen-tial growth	$Y_0 = 0$	$A = 0.01624$	$t = 0.08794$	0.81693	X^2/dof = 0.12385	32	<0.0001
Ψ_6/quadratic	–0.00997	0.26457	–0.2657	0.9887	–0.0014	32	<0.0001

Thus, the results given in Table 4 reveal that any of the six density-independent microwave permittivity functions may be used as moisture calibration functions for soybean bulk as well as seed samples for a newly fabricated moisture meter (Nelson, 2008) and these functions leave a scope for their possible use in other grains and seeds so that, if possible, universal type of calibration equation(s) may be found.

4 Conclusions

Most of the presented moisture-dependent density-independent microwave permittivity functions may be useful in the calibration of microwave moisture meters. In this regard, the most suitably fitted plot may be used as a moisture calibrator for soybean samples if the samples undergo a gradual and systematic moisture variation.

Nomenclature

In all the equations used in the text, the symbol representation is as follows:

ε_r = relative permittivity of the mixture

$\varepsilon_H = \varepsilon_1$ = relative permittivity of air = 1

$\varepsilon_I = \varepsilon_2$ = relative permittivity of the particles (subscript denotes inclusion)

f_1 = volume fraction of air

f_2 = volume fraction of particle (= ratio of bulk density to seed density)

For the air-particle binary mixture,

$$f_1 + f_2 = 1.$$

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