A new analytical approach to predicting moisture contents of corn kernels through microwave permittivity data

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Abstract-In the present work two models namely, quadratic and cubic, for the variation of relative permittivity and dielectric loss factor of shelled yellow-dent field corn, *Zea mays L.* with decimal moisture content at a microwave frequency of 2.45 GHz have been proposed by the authors. In an attempt to reduce the randomness in moisture-dependent variation of intrinsic dielectric properties of grains and cereals ,attributable to bulk density variation, a new term called moisture specific volume{ratio of kg water per kg of total mass to bulk density of the test material} is introduced in the present work. The data of results for relative permittivity and loss factor have been derived from the works of S.O. Nelson and the models chosen for comparison with the present models are also due to S.O. Nelson. The evaluation of constants for the models has been done using the method of Least-Squares-Fit for nonlinear regression analysis. With the values of coefficients of determination (r^2) too close to unity (≈ 0.99), except for cubic model for loss factor ($r^2 \approx 0.89$), and lower average percentage errors, excepting the cubic model for loss factor having average errors ≈ 19.49 %, both the present models and both dielectric parameters compare the present models favorably with the established models.

Index Terms: Relative Permittivity, Dielectric loss factor, Nonlinear regression, Microwave frequency. moisture specific volume ,Corn.

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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 moisture content of grains which help in preventing the spoilage of large blended lots stored in elevators, ships or mills[1-2]. It is why; 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 Shelled Yellow-dent field corn (***Zea mays L.)*** using the data of results for them at a fixed frequency of 2.45 GHz at 24^0C to present empirical expressions which allow predictions of permittivity and loss factor. The data of results for relative permittivity have been taken from Table 5 of Nelson's Paper5 and the data of approximate values of dielectric loss factor at the same frequency and temperature have been derived from the graphical representation of the data points as contained in Fig.12 (b) of **Nelson's** another paper[1]. The values of bulk density at the six moisture contents from 10.3 % to 33.4 % were derived from the bulk density – moisture relationship for corn as presented by equation (4) of Nelson's Paper[6]. Data for dielectric properties have been chosen at microwave frequency keeping in view the fact that hazardous ionic conductivities and bound-water relaxation effects disappear almost completely in this range of frequency. Thus microwaves offer a nondestructive, sensitive and feasible method for determining the water content of grain samples.

2. Experimental

The general quadratic and cubic models connecting dielectric constant, moisture content and frequency of operation were used for their comparison with the corresponding new models proposed in the present study.

General form of the equations is

$$\varepsilon' = [1+\{A_2 - B_2 \log f + (C_2 - D_2 \log f)M\} x\rho]^2 \qquad 1$$

$$\text{And } \varepsilon'' = [1+\{A_3 - B_3 \log f + (C_3 - D_3 \log f)M\} x\rho]^3 \qquad 2$$

The only one equation for the dielectric loss factor available for comparison is of the form:

$$\varepsilon'' = 0.146\, \rho^2 + 0.004615\, M^2 \rho^2\, [0.32 \log f + 1.743/\log f - 1] \qquad 3$$

Where $\rho \equiv \rho_b$ = bulk density of the material in gram x cm^{-3}

M =100m = % moisture content, wet basis

f = frequency of operation in MHz.

m = decimal moisture content.

The values of constant viz., A_2, B_2, C_2, D_2 or A_3, B_3, C_3, and D_3 of equations 1 and 2 for Shelled Yellow-dent field corn were taken from Table 6 of Nelson's paper[2].

Based on the observations of almost linear plots obtained from 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.

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.

The proposed models are:

The proposed models are: -

(Quadratic model)

$$\varepsilon' = a\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix}^2 + b\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix} + K_1 \qquad 4a$$

$$\varepsilon'' = c\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix}^2 + d\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix} + K_2 \qquad 4b$$

(Cubic model)

$$\varepsilon' = a\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix}^3 + b\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix}^2 + c\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix} + K_1 \qquad 5a$$

$$\varepsilon = d\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix}^3 + e\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix}^2 + f\begin{Bmatrix} m \\ m_d \\ m_v \end{Bmatrix} + K_2 \qquad 5b$$

The value of the constant K_1 was taken as the average of the values of relative permittivity derived from equations (1) and (2) by putting M=0. The value of bulk density corresponding to M=0 (ρ_0) as taken from equation (4) of Nelson's Paper[6], is equal to 0.6829. The value of K_2 was equal to the value of loss factor corresponding to M=0, which is given by Equation 3 in the form

$K_2 = (\varepsilon'')_{M=0} = 0.146\ \rho_0^2 = 0.146 \times (0.6829)2 = 0.06808$ 6

The average value of K_1 was found to be equal to 1.4456 from the data of results for relative permittivity at different decimal moisture contents. The constants for the first part of each of the two sets of models as envisaged in Equations 4 and 6 were evaluated, using the method of least-squares- fit for nonlinear regression. The same method was adopted for the second part of each of the two models given by equations 4(b) and 5(b), using the data of results for dielectric loss factor derived from the works of S.O. Nelson[1], as referred to earlier in the text.

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 ten dielectric mixture equations .

Brief Introduction of the Dielectric Mixture Equations Used

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

$$\ln \varepsilon_r = \sum_{i=1}^{n} f_i \ln\varepsilon_i \qquad 7a$$

(for n-component mixture)

Thus, for an air-particle binary mixture

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

where

ε_r = permittivity of mixture

f_1 = volume fraction of air

ε_1 = permittivity of air = 1 ⇒ln ε_1=0

f_2 = volume fraction of the particles,

with f_1+f_2 = 1, and

ε_2 = permittivity of the particulate materials.

Also, ε_2 = Exp [$1/f_2 \ln \varepsilon_r$] 7c

(ii)Taylor's formula for random angular distribution of needle -

$$3\varepsilon_r \frac{(\varepsilon_r - \varepsilon_H)}{f} = (\varepsilon_I - \varepsilon_H).(2\varepsilon_I + \varepsilon_r) \tag{8a}$$

Where

, ε_I = permittivity of the inclusion

= ε_2 (for the present case)

ε_H = permittivity of the host (air) = 1

The above expressions finally give:

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

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

(iii) ***Taylor's formula for random angular distribution of disks, Taylor -***

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

On similar pattern as above, one gets

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

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 $l << \lambda$, where l is the large dimension of the ellipsoid and λ is the wavelength of the wave. Also, the average field approximations are valid only for $f^2 << 1$.

(iv)Lewin's formula

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:

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

Which in the present case simplifies to

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

Thus the upper limit to the usefulness of the above formula should be $f \leq \pi/6$. 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

$$\varepsilon_r = \frac{\varepsilon_H\left[\varepsilon_H + D(1-f) + f\right]}{\left[\varepsilon_H + D(1-f)\times(\varepsilon_I - \varepsilon_H)\right]} \quad \text{11a}$$

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

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

$$\varepsilon_r = \frac{\left[1 + \{D(1-f) + f\}.(\varepsilon_r - 1)\right]}{\left[1 + D(1-f).(\varepsilon_2 - 1)\right]}$$

$$\Rightarrow \varepsilon_2 = \left[\frac{(\varepsilon_r - 1)}{\{f - D(1-f).(\varepsilon_r - 1)\}}\right] + 1 \quad \text{11b}$$

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**

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

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 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, $\varepsilon_H = 1$ and $\varepsilon_I = \varepsilon_2$ as before, and we find that:

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

which finally gives:

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

(vii) *Formula obtained from* ***Effective Medium Theory***

$$\varepsilon_r = \frac{\varepsilon_H\left[(1+2f)\varepsilon_I + 2\varepsilon_H(1-f)\right]}{\left[\varepsilon_1(1-f) + (2+f)\varepsilon_H\right]} \quad \text{13a}$$

$$\varepsilon_2 = \frac{\left[(2+f)\varepsilon_r - 2(1-f)\right]}{\left[1 + 2f - \varepsilon_r(1-f)\right]} \quad \text{13b}$$

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.

(viii) **Skipetrov formula**

$$\varepsilon_{eff} = \varepsilon_1\left[\frac{1 + \{3f_2(\varepsilon_2 - \varepsilon_1).\}}{\{\varepsilon_2(2+f_2) + \varepsilon_2(1-f_2).\}}\right] \quad \text{14a}$$

For the present case

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

The equation finally gives:

$$\varepsilon_r = 1 + \frac{[3f(\varepsilon_2 - 1)]}{[(2+f) + \varepsilon_2(1-f)]} \quad \text{14b}$$

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.

(ix)***Modified Cule and Torquato equation***

$$\varepsilon eff = \varepsilon_I[1 + 2a^2\beta / (b^2 - a^2\beta)] \quad 15a$$

with β = (ε_2- ε_1)/(ε_2+ ε_1), where a is the radius of the core having permittivity ε_1, b the radius of the surrounding concentric shells having a permittivity equal to ε_2 so that f = $(a/b)^2$, yielding

$$\varepsilon_2 = [\{(f-1) + (f+1)\varepsilon_r\} / \{(f+1) + (f-1)\varepsilon_r\}] \quad 15b$$

(x)***Knott equation :***

$$\varepsilon_{eff} = \varepsilon_2[1 - \{(\varepsilon_2 - \varepsilon_1)(1-f)\} / \{\varepsilon_1 + (\varepsilon_2 - \varepsilon_1)(1-f)^{1/3}\}] \quad 16a$$

$$\varepsilon_2 = \frac{[-\{\varepsilon_r(1-f)^{1/3} - (2-f)\} + \sqrt{\{\varepsilon_r(1-f)^{1/3} - (2-f)\}^2 - 4(2-f)\varepsilon_r}}{2(2-f)} \quad 16b$$

Using any measured value of ε_r , the corresponding value of volume fraction of the particle, f2= (f), the value of the permittivity of the particles, ε_2 (= ε_2, 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 (say) for the quadratic or the cubic model, as the case may be, were used to compute the value of m, (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), 2 ,,were calculated. Thus one gets the values of 2 and 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 2 and 2 as functions of md and mv for both types of the proposed models. It was expected to achieve the estimates of 2 and 2 of shelled yellow-dent field corn as functions of m, m**d** and m**v**.

Table 1- Data of results for relative permittivity, loss factor and bulk density of Shelled Yellow-dent field corn, ***Zea mays L.*** measured at 2.45 GHz and 240C at six moisture contents, wet basis.

Moisture Content %, wet basis	Bulk density in g x cm3	Relative permittivity ε´	Dielectric loss factor ε´´
10.3	0.74	2.47	0.30
12.2	0.74	2.59	0.37
17.7	0.71	3.2	0.63
19.5	0.70	3.59	0.69
22.9	0.68	3.98	0.80
33.4	0.64	5.25	0.85

Table 2- Data of evaluated constants for the different models for complex permittivity of corn, (ZeaMays. *L.*) corresponding to 24^{0}C and 2.45GHz .

	Nelson Model		Model from Present Study	
Models	Quadratic	cubic	Quadratic	cubic
(A)Models with decimal moisture content (m)	A_2=0.685 B_2=0.1212 C_2=0.0674 D_2=0.0058	A3=0.466 B3=0.0770 C3=0.0342 D3=0.0023	a_2= 7.2307 b_2=9.3904 c_2=7.90057 d_2=1.08605 K_1=1.4456; K_2=0.06808	a_3= -36.5222 b_3=24.7005 c_3=7.2757 d_3= -71.91018 e_3=31.96729 f=0.29947 K_1=1.4456;K_2=0.0680
(B)Models with moisture density (m_d)	……………	……………	a_2=37.69562722 b_2=10.00111702 c_2=2.204280224 d_2=4.436129314 K_1=1.4456;K_2=0.0682	……………..
(C)Models with moisture specific volume (m_v)	……………	…………	a_2=0.256539712 b_2=7.43198846 c_2=2.089000771 d_2=2.654232321 K_1=1.4456;K_2=0.0682	…………………

Table 3(a)--Comparative Performances of different models for the variation of relative Permittivity with moisture content of Corn(Zea Mays L) at 24^{0}C and 2.45 GHz

Nelson's Model	Present Model

Quadratic Model(Q.M)		Cubic Model(C.M)		Quadratic Model(Q.M)		Cubic Model(C.M)	
Predicted values	r^2/Mean % error	Predicted values	r^2/ Mean % error	Predicted values	r^2/ Mean % error	Predicted values	r^2/ Mean % error
2.47 2.67 3.23 3.40 3.71 4.79	1.000 4.18	2.48 2.71 3.23 3.40 3.72 4.84	1.000 3.23	2.49 2.70 3.33 3.55 3.98 5.39	0.999 2.17	2.42 2.63 3.30 3.53 3.97 5.27	0.997 1.57

Table 3(b): -Comparative Performances of different models for the variation of loss-Factor with moisture content of Corn (Zea Mays L) at 24^{0}C and 2.45 GHz

Nelson's Model		Present Model			
		Quadratic Model(Q.M)		Cubic Model(C.M)	
Predicted values	r^2/ Mean % error	Predicted values	r^2/ Mean % error	Predicted values	r^2/ Mean % error
0.24 0.30 0.51 0.59 0.73 0.31	0.990 22.15	0.26 0.32 0.51 0.58 0.73 1.31	0.990 3.30	0.36 0.45 0.72 0.81 0.95 1.01	0.886 19.49

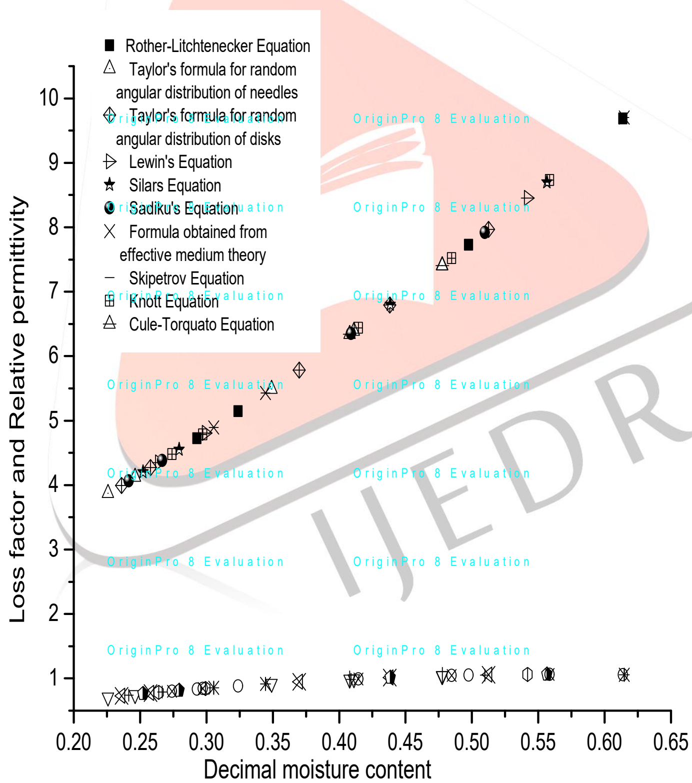

Fig 1

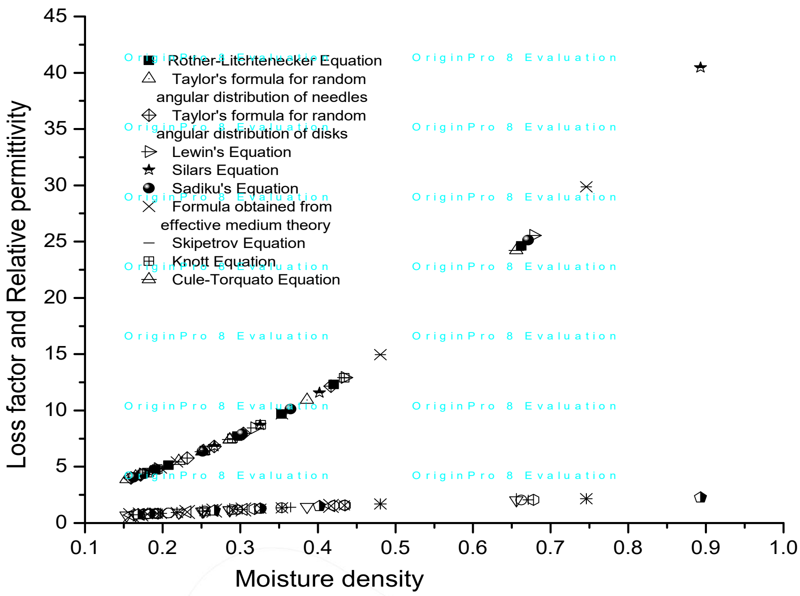

Fig 2.

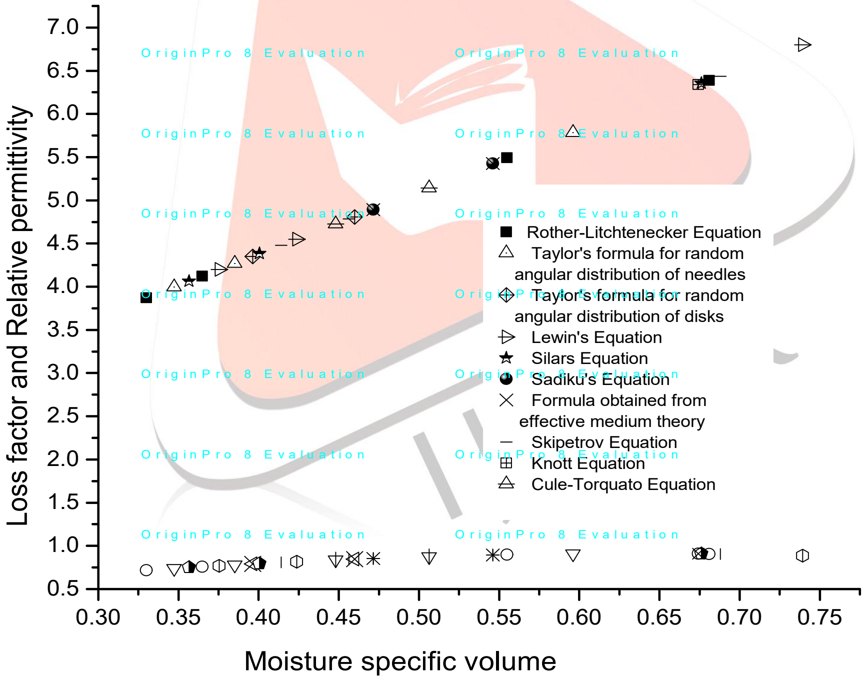

Fig 3..

3 Results and Discussion

Data of results for relative permittivity, loss factor and bulk density of shelled yellow-dent field Corn at 2.45 GHz and 24^{0}C and at six moisture contents are illustrated in Table 1 and the evaluated Constants for different proposed models have been listed in Table 2. Further, the quantitative Comparative performances of the present models and those of Nelson are reported in Table 3(a) and 3(b).The coefficients of determination (r^2) and average percentage errors of prediction for each of the different models have also been reported.

Examination of data in Table 3 reveals that both quadratic and cubic models of Nelson relating relative permittivity to decimal moisture content generally predicted almost the same values, excepting a few instances where they differed by more than 5%. The average error of prediction over all moisture contents was 4.18 % for the quadratic model and 3.23 % for the cubic model. The corresponding average errors of prediction for the present two models are 2.17 % and 1.57 %. The average percentage error of prediction in Nelson's solitary model for dielectric loss factor against moisture content is too high ≈ 22.15 %. Similar is the order of deviation in the newly proposed cubic model, being ≈ 19.49 %. On the contrary, the deviation is too small ≈

3.30 % with the newly proposed quadratic model. The r^2-values for all the models for relative permittivity are ≈ 0.99 to 1.00 and thus all the models show good fitting with experimental results. The r^2-values for Nelson's model for dielectric loss factor and the present quadratic model are ≈0.99, but the present cubic model shows a bit poorer fitting having $r^2 \approx 0.89$.Graphical presentation for the 2 and 2 as function of data points for decimal moisture content(Fig 1),moisture density(Fig 2) and moisture specific volume(Fig 3) dependent quadratic and cubic model.
Thus, on the basis of present study, it may be opined that the new quadratic models both for the relative permittivity and loss factor, proposed in the present study provide better performance as compared with others in predicting moisture dependence of relative permittivity and dielectric loss factor at the chosen range of microwave frequency.

4 Conclusion
The moisture dependence of relative permittivity and dielectric loss factor of shelled yellow-dent field corn,(***Zea mays L.***) over moisture ranges of 10 to 33 percent at 2.45 GHz and 240C can be accurately represented by second and third order polynomial equations, both dielectric parameters showing slowly increasing trend with the increase of moisture content. The results derived from the models are indicative of the fact that these equations should be generally useful for predictive purposes in most practical applications.

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