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ORIGINAL ARTICLE

Prediction model for moisture determination of Indian wheat based on electrical properties variations

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Keywords
electrical properties variation; moisture content; moisture prediction model; partial least square regression.

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Abstract

Introduction Measurement of moisture is an important aspect in harvesting, drying, storing and processing of grains. *Objective* The objective of this study was to develop a new method for the moisture measurement of *Triticum aestivum*, a cultivar of Indian wheat grain, by using measurements obtained by electrical spectroscopy. *Methods* The relationship between electrical properties of Indian wheat and moisture content, with range 7.96% to 31.58%, was investigated within frequency range of 1 KHz to 1 MHz. An investigation of the effect of frequency characteristics on moisture content was performed and the best frequency was chosen for further investigations. Partial least square regression technique was applied to illustrate the dependence of electrical properties viz. capacitance, impedance, and dissipation factor on frequency and moisture content. *Results* Moisture prediction model using these properties was developed and it was observed that the new method increased accuracy of moisture measurement as compared with that obtained using a single parameter. The experimental samples were divided into three classes – low, medium and high moisture, and samples were reanalyzed to investigate range-specific precision of selected frequency. *Conclusion* The developed model can estimate the moisture content within performance expected from a commercial moisture meter.

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Introduction

Moisture content (MC) is measured when the farmers need to know if their crops are ready for harvest or not. If MC is too low, there is a risk of damage from kernel breakage or shattering losses. The grain should be harvested as soon as possible to avoid potential losses in the field from bad weather. Grain that is too high in MC is subject to attack by grain storage fungi and stored-grain insects. The farmers also need to know the MC to decide if crops need to be dried before they can be safely stored. If they desire to sell their crops directly to the grain elevator, the MC must also be determined, because the selling price depends on the MC. After the grain has been safely harvested and stored, MC comes into play again when it is to be processed into flour, feed or making other products. Therefore, better information on the moisture levels of products, such as cereal grains, can be of significant value in maintaining the quality of allied products and preventing losses and contamination. As standard methods for MC determination in grains involve tedious and lengthy laboratory procedures, rapid method for moisture measurement in grains is essential. Hence, studies on electrical measurements have been carried out for a long time to provide rapid techniques for grain moisture measurement. Briggs (1908) discovered a linear relationship between the dc electrical resistance of wheat and its MC, and since then many types of electrical moisture meters were developed to rapidly determine the MC of different types of grain. The first quantitative data on the dielectric properties of grain were reported for barley along with a method for reliable measurement of these properties in the 1–50 MHz frequency range (Nelson *et al*., 1953). Quantitative dielectric properties data were soon reported in the USSR for wheat and other grain and crop seeds (Knipper, 1959). Extensive measurements on grain and crop seeds in the 1–50 MHz range were finally summarized and made available for use in electric moisture meter design and other applications (Nelson, 1965). Several years later, moisture dependence of the dielectric constant of aqueous materials was established (Sokhansanj & Nelson, 1988) and this led to the development of moisture meters that use certain dielectric related measurements for moisture determination. A method was developed earlier to measure the MC of peanuts using impedance and phase angle at 1 and 5 MHz of a parallel plate capacitor holding the corns between the plates (Kandala *et al*., 2007). By this method, the predicted MC values for 93% of the samples tested were found to be within 1% of the standard MC values. Mizukami *et al*. (2006) developed a new method for the moisture measurement of tea leaves by using measurements obtained by electrical spectroscopy. Performance evaluation of digital grain moisture meter for Indian wheat using capacitance variation has also been reported recently (Babankumar & Thakur, 2011). An evaluation of calibration performance of laboratory-developed moisture meter for Indian wheat with two different techniques has been reported (Babankumar *et al*., 2011). Thakur *et al*. (2011) carried out studies on electrical properties of wheat as a function of MC [14.3% to 29.38%, wet basis (wb)] for frequency range of 100 kHz–10 MHz. Although a lot of work has been carried out in MC determination of grains using electrical properties, there is still a growing demand for developing rapid, reliable and cost-effective techniques for hassle-free sensing and measurement of MC in grains. Too little quantitative data analysis for the Indian short wheat grain has been reported so far in the low frequency spectra. Further, multivariate studies involving electrical properties other than dielectric constant have been rarely carried out for moisture determination prediction model on Indian short wheat grain. Also, no work has so far been reported wherein studies are carried out for samples divided into different moisture ranges of grains and hence there is a scope of developing moisture range specific prediction model.

The present paper reports a novel approach of moisture measurement of Indian short wheat grain by studying variations in electrical properties of the grain. The relationship between the electrical properties such as capacitance (C), impedance (Z), and dissipation factor (DF) of the Indian wheat and MC of wheat was investigated within low frequency range from 1 KHz to 1 MHz to develop an accurate multivariate prediction model by using partial least squares analysis. The investigation of the effect of frequency characteristics on MC prediction was also performed and the best frequency was chosen for further investigations. After studying the variations in electrical properties using partial least square analysis technique at that frequency, a prediction model was developed to predict the MC of wheat samples in the range of 7.1% to 34.5%, wb. The new method increased the accuracy of moisture measurement as compared with that obtained using a single parameter. The experimental samples were also divided into three classes depending on MC – low moisture, medium moisture and high moisture – and subsequently, the samples were reanalyzed.

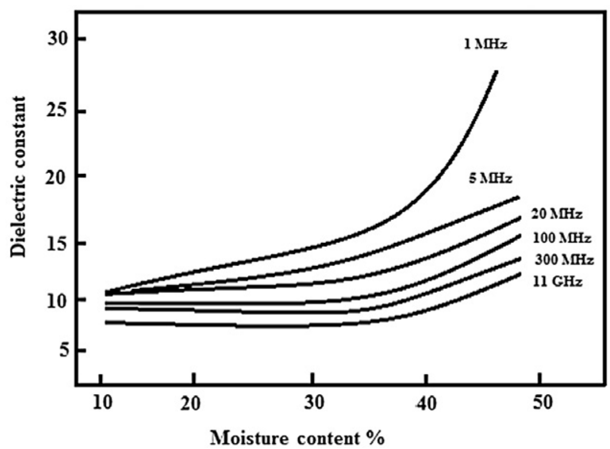

Figure 1 Moisture dependence of the dielectric constant of shelled yellow-dent field corn at indicated frequencies.

Theoretical considerations

Nelson (1979) investigated the moisture dependence of the dielectric constant of shelled, yellow-dent field corn (maize) at different frequencies from 1 MHz to 11 GHz. Relationships established between the dielectric constant and MC of corn by the experimental data are shown in Figure 1.

As the increase in dielectric constant with MC was more pronounced at 1 MHz than at 5 MHz, the separation of the two curves increased with increasing moisture. Thus, the difference in the values of the dielectric constant at the two frequencies should provide an estimate of the MC. It was shown earlier that if the capacitance of a parallel-plate capacitor with a material of thickness d and projected area A_k between its plates is C1 and C2 at any two frequencies, then

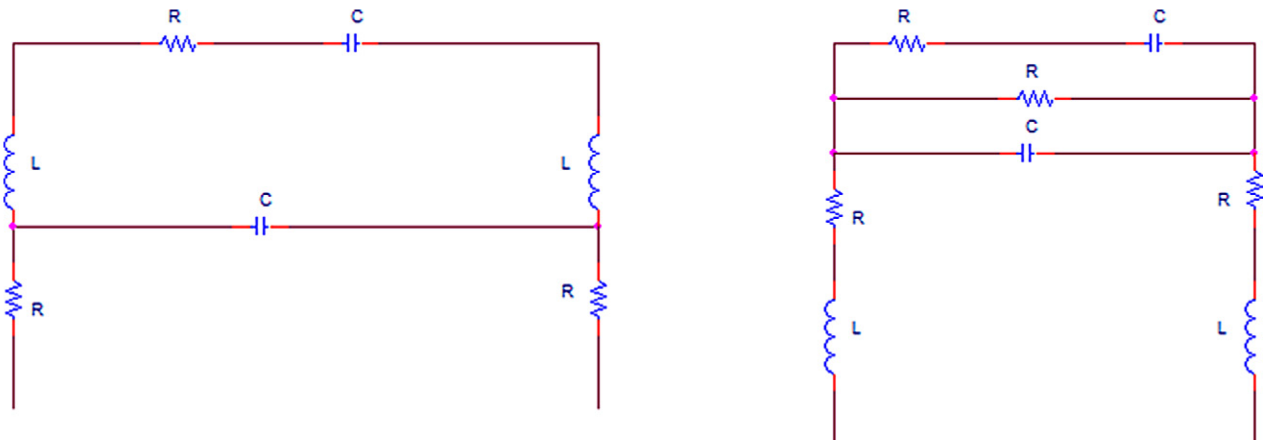

Figure 2 Capacitor with parasitic represented by an electrical equivalent circuit.

$$\varepsilon_{r1} - \varepsilon_{r2} = (C_1 - C_2)d/(A_k\varepsilon_0) \quad (1)$$

where ε_r is the dielectric constant of the material at the measurement frequency, and ε_0 is a constant, the permittivity of free space. Thus, if $(\varepsilon_{r1} - \varepsilon_{r2})$ is a good estimator of moisture, then $(C_1 - C_2)$ should also be a good estimator. However, a real-world capacitor contains many parasitic as shown in Figure 2.

Hence, it becomes necessary to measure not only capacitance but other related parameters such as Z, resistance (R), reactance (X), DF and C in order to develop an accurate prediction model for moisture measurement in grains.

Materials and methods

Grain sample preparation

An appropriate number of samples for *Triticum aestivum*, a cultivar of Indian wheat grain, were prepared to conduct studies at 1 KHz–1 MHz frequency band at room temperature. In preparing conditioned samples, a fixed quantity (150 g) of grain was taken after weighing. The broken kernels and foreign materials were removed manually. Distilled water was added to the sample to raise its MC to predetermined calculated levels (7.1–34.5%, wb). The sample was stirred during the addition of water and the conditioned samples were stored in sealed jars at 2–4 °C in cold storage for at least 4–5 days, before its electrical properties were measured. During this conditioning period, the sealed jars were shaken periodically to aid the uniform distribution of moisture. The MC of each sample was determined by standard dry oven technique by grinding 5–10 g of the sample and drying it for 2 h at 130 °C. Two hot-air dry ovens were used during the experimentation period to increase experimental throughput and avoid time lag. Refrigerated samples in sealed jars were permitted to reach room temperature (22 °C) before opening them for electrical measurements. Altogether, 19 samples covering a range of 7.1–34.5% (wb) moisture values were prepared for the room temperature studies.

Experimental setup

For the measurement of electrical properties, 150 g of each sample of Indian wheat was used. The sample holder consists of two coaxial cylinders, serving as a dielectric cell (Figure 3). The outer cylinder is 58 mm long, with an internal diameter of 90 mm and has a wall thickness of 2 mm. The inner cylinder has outer diameter of 45 mm. These cylinders are joined on the single plate of Teflon. In order to improve the quality of sensing cell, the cylinders are given anodizing material treatment to avoid capacitor leakage charging current. It forms a concentric cylindrical type dielectric cell, joined with shielded coaxial cable of low capacitance. These two leads from cylinder are connected to the two ports of LCR meter.

The measurements are significantly influenced by the residual impedance and admittance of electrodes as well as the cable and electrodes. For increasing the accuracy of the measurements, it is essential to apply corrections to the electrical measurement. There are two calibration operations that automatically correct the measurements obtained using an LCR meter. The calibration compensation was performed for the cylinder test leads before starting electrical measurements in order to avoid errors against terminal connections and residuals. The sample holder was shielded in order to

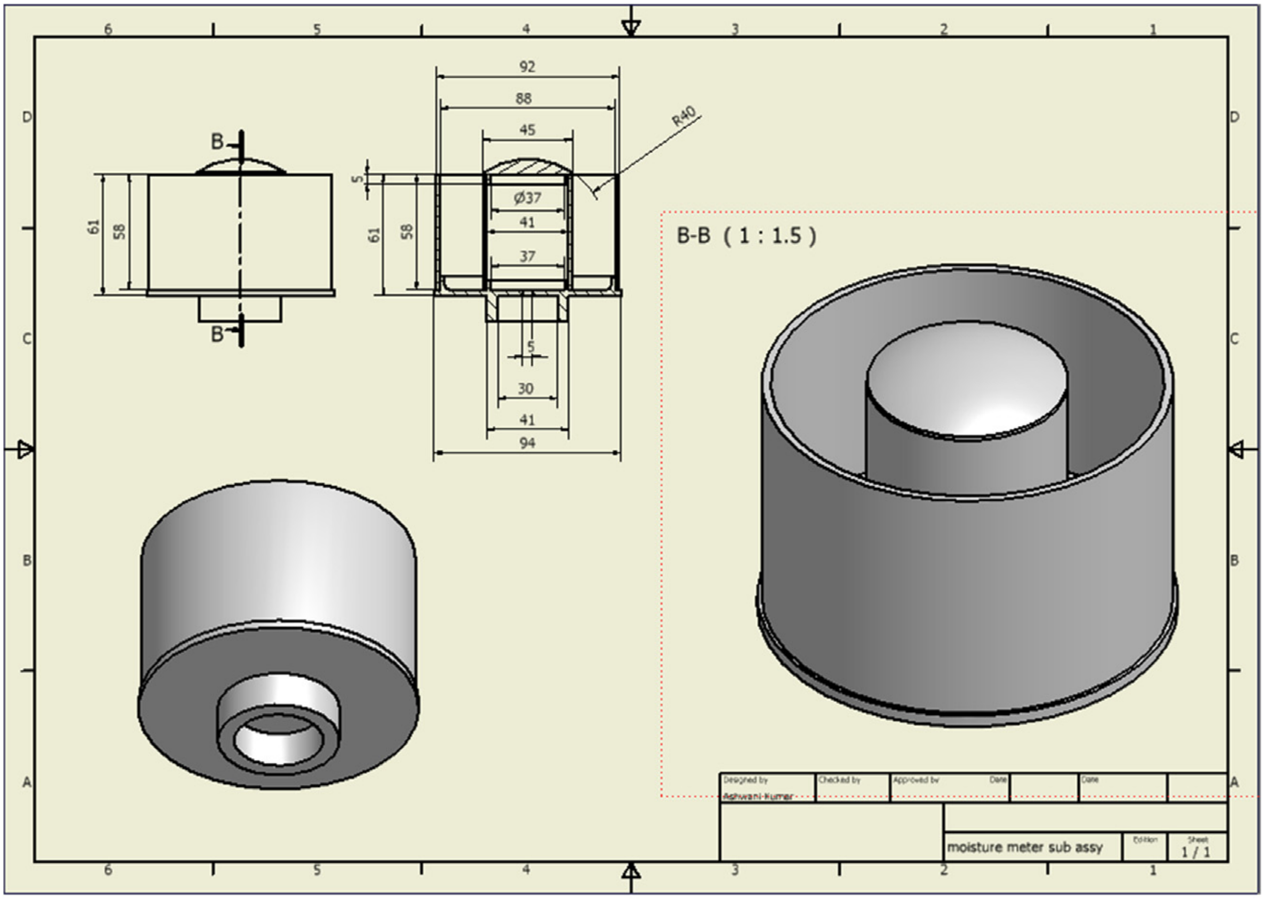

Figure 3 Sampler holder design.

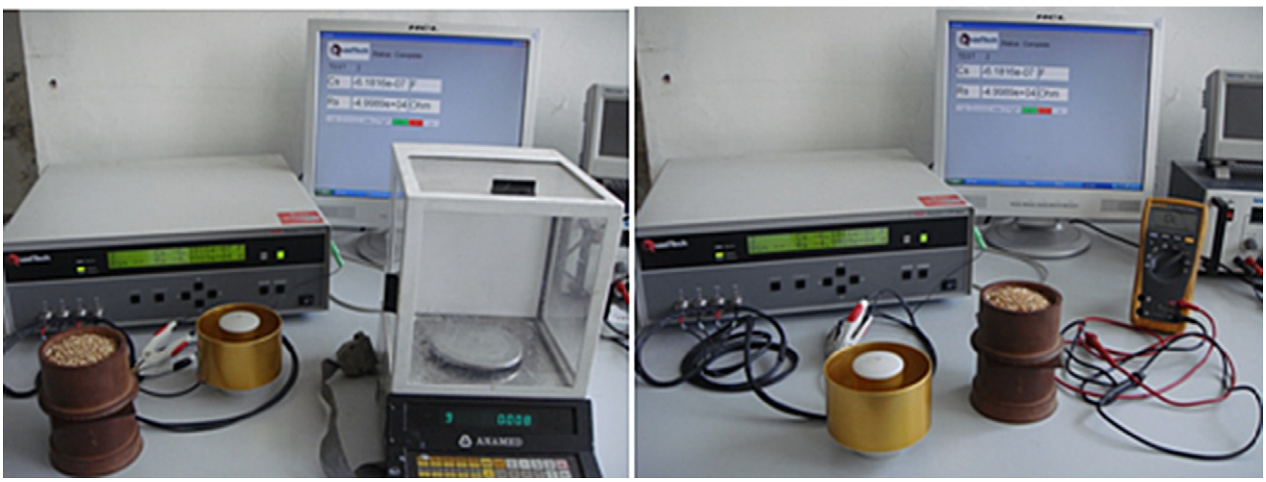

Figure 4 Experimental arrangement.

avoid the effect of stray fields. An arrangement of experimental setup to carry out the present study is shown in Figure 4. The electrical Z, C and D were measured using Quadtech 1920 model (Quadtech, Marlborough, MA, USA), which is a Precision LCR meter. The measurement data were automatically transmitted from LCR meter to a personal computer (PC) through an interface which connects PC and instrument serially.

Table 1 Statistical fitness measure values at each frequency

Frequency (Hz)	RMSEC (calibration)	RMSEP (validation)	Correlation (calibration)	Correlation (validation)
1000 (F1)	1.00384	1.26124	0.98961	0.98386
1585 (F2)	1.07434	1.28437	0.98809	0.98293
2512 (F3)	1.08885	1.43884	0.98776	0.97933
3981 (F4)	1.80254	2.05872	0.96608	0.95553
6309 (F5)	1.68773	1.93837	0.97033	0.96068
9999 (F6)	1.44825	1.7721	0.97824	0.96725
15847 (F7)	1.47941	1.71972	0.97728	0.96918
25116 (F8)	1.37573	1.60693	0.98039	0.97314
39806 (F9)	1.26424	1.48675	0.98346	0.97724
63088 (F10)	1.14251	1.33619	0.98651	0.98151
99988 (F11)	1.01485	1.17544	0.98937	0.98572
158470 (F12)	0.91501	1.03585	0.99137	0.98893
251158 (F13)	**0.8879**	**0.98218**	**0.99188**	**0.99005**
398059 (F14)	0.9787	1.10797	0.99012	0.98735
630881 (F15)	1.1247	1.33664	0.98693	0.98169
999879 (F16)	0.94194	1.18385	0.99085	0.98607

Statistical analysis by the partial least squares method was performed using The Unscrambler X software on the measurement data (Camo Software, Oslo, Norway).

Results and discussions

Moisture dependence of electrical properties

First, in order to find a suitable measurement frequency for this prediction model system, the dependence of Z, R, X, DF, phase angle (θ) and C on the MC of the Indian wheat was examined by the partial least squares method in the frequency range of 1 KHz to 1 MHz. This analysis could not well establish the mutual relationship between resistance and the MC and X and the MC at any frequency. Also, it reveals that the MC can be measured by a logarithmic function of capacitance (ln C), DF and Z more reliably.

$$\mathrm{M} = \mathrm{f}(\ln \mathrm{C}, \mathrm{DF}, \mathrm{Z}) \tag{2}$$

Frequency dependence of electrical properties of grains

Frequency is one of the important factors that affect the electrical properties of grain (Nelson, 1979, 1982). Most conventional electrical grain moisture meters operate in the 1-to-20 MHz range. Consequently, measurements with these meters are based on the relationships between grain moisture and electrical properties of the grain in that frequency range. In order to develop the empirical relation between moisture and electrical properties, partial least square regression technique was applied to maximize scores for the variation of electrical properties in correlation to moisture and was analyzed at all frequencies. The data were standardized after observing descriptive statistics, and full cross-validation as well as standard test set validation were applied in order to develop grain moisture prediction model. Frequency-dependent selection of prediction model for best frequency was analyzed by studying characteristic of correlation coefficient between the standard value and the predicted value. Also, root mean square error (RMSE) was compared for both calibration and validation data. Table 1 shows the comparison of RMSEC, RMSEP and correlation values for calibration and validation data.

The best correlation for calibration and validation data is found at F13 frequency, that is, 251.158 KHz. Also, the RMSE values for calibration and validation are found to be least at this frequency value. Therefore, the frequency of 251.158 KHz has been chosen for the study of electrical properties of wheat and subsequent development of moisture prediction model.

Moisture prediction using electrical properties of Indian wheat

Using capacitance alone

A reverse prediction equation for measuring the MC using capacitance was developed at 251.158 KHz:

$$\mathrm{M} = 24.37198 \times \ln(\mathrm{Cp}) + 604.824646$$
$$\left(R^2{}_{\mathrm{calibration}} = 0.989539, R^2{}_{\mathrm{prediction}} = 0.986644\right)$$

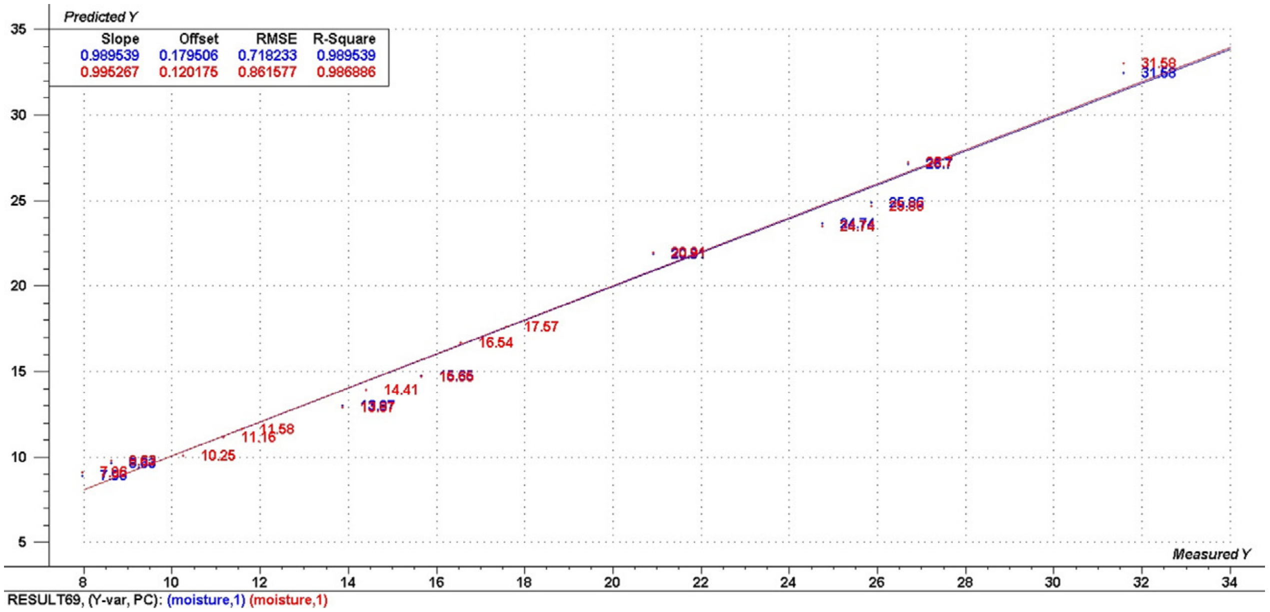

Figure 5 Predicted versus measured moisture when capacitance alone is used.

The result of prediction model using capacitance is shown in Figure 5.

From Figure 5, it can be observed that $R^2_{calibration}$ and $R^2_{prediction}$ are 0.989539 and 0.986644, respectively, and $RMSE_{calibration}$ and $RMSE_{prediction}$ are 0.718233 and 0.861577, respectively, when C alone is used for the prediction.

Prediction model using C, Z and DF

C, Z and DF were combined to predict the MC of the of the grain samples using PLS regression model as shown in Figure 6.

A regression analysis between the MC and the electrical parameters viz. ln C, Z and DF at 251.158 KHz frequency gives rise to an empirical relationship with a correlation coefficient of 0.99689. The PLS regression model analysis below mentioned moisture prediction equation:

$$M = 100.2748 + 6.4696\ DF + 3.3551 \ln C - 0.0003Z \qquad (3)$$

It can also be observed that the plateau has reached a single factor (1 factor) and the explained Y-variance is very high (99%). This signifies that the developed model is very good and can be relied upon for precise moisture prediction results.

Predicted versus measured plot of moisture (calibration)

The predicted versus measured plot of moisture for calibration data is shown in Figure 7.

It shows a straight line relationship between predicted and measured values, with slope and correlation very close to 1, that is, 0.99379 and 0.99689, respectively.

Predicted versus measured plot (validation)

The predicted versus measured plot of moisture for validation data is shown in Figure 8.

It also shows a straight line relationship between predicted and measured values, with both slope and correlation values very close to 1, that is, 0.9907 and 0.99567, respectively.

Correlation loading plot

As can be seen in the correlation loading plot in Figure 9, Log C and DF have a high positive correlation with moisture, whereas Z and moisture are negatively correlated. The most significant predictor variables have been marked by Martin's uncertainty test criteria and are shown encircled. Moreover, model is best fit for factor 1, whose explained variance is 99%. Thus, electrical parameters at selected frequency exhibit high degree of certainty and precision in the present model for moisture determination of Indian wheat grains.

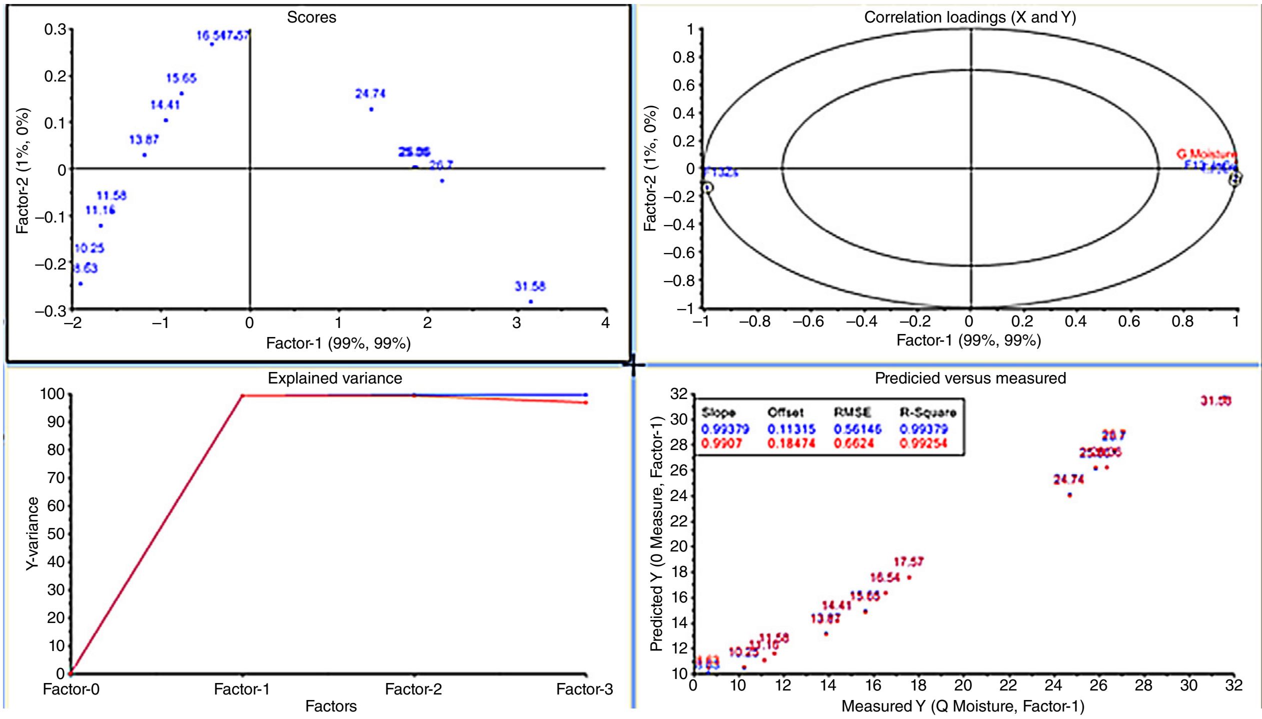

Figure 6 PLS regression model using three electrical parameters.

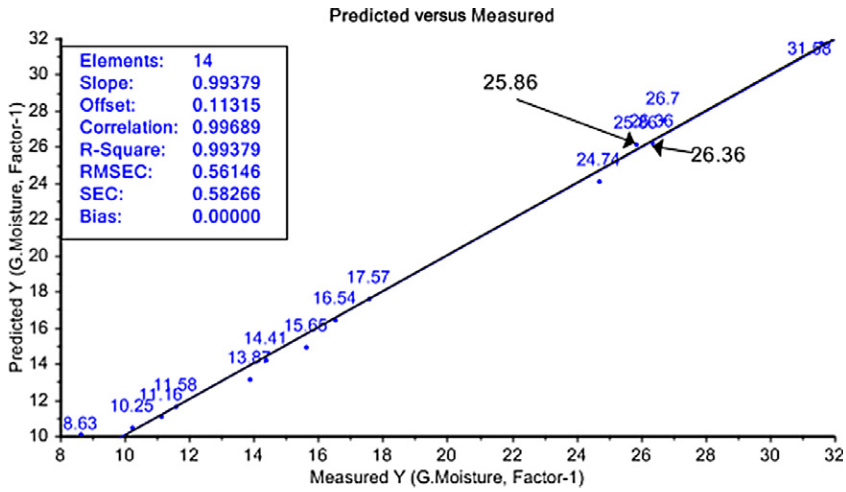

Figure 7 Comparison of oven and predicted moisture content values for calibration set.

Scores plot

It can also be observed from the scores plot in Figure 10 that the sum of the explained variances for the two components is large (X-expl: 100%, 0% and Y-expl: 99%, 0%) and the plot shows a large portion of the information in the data, so the relationship can be interpreted with a high degree of certainty and can be relied upon for future predictions of MC of unknown samples.

Fitness measures for the calibration and validation sets

The fitness measures for the calibration set are shown in Table 2. The calibration set has an R^2 value of 0.99379 and the standard error of calibration was 0.58266.

Similarly, for the validation set, the fitness measures are shown in Table 3.

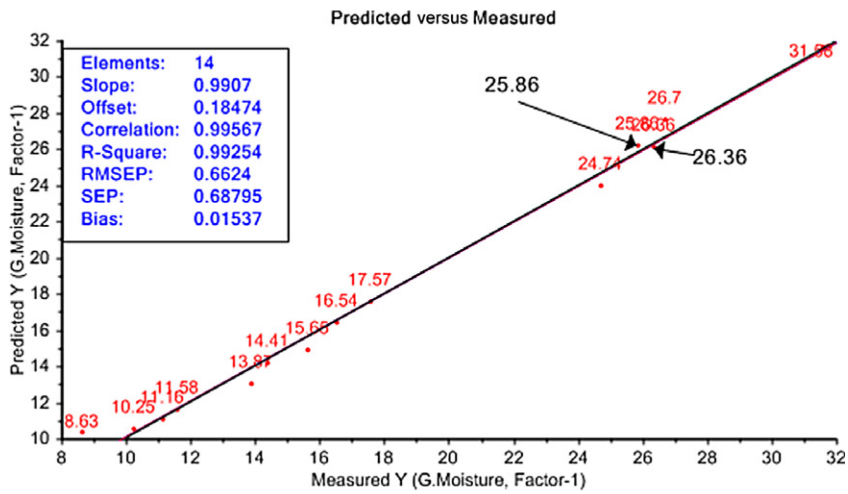

Figure 8 Comparison of oven and predicted moisture content values for validation set.

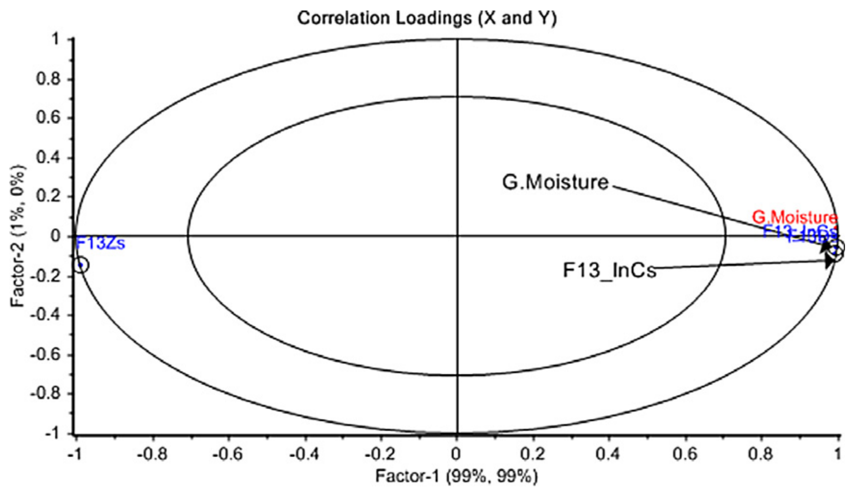

Figure 9 Correlation loadings plot.

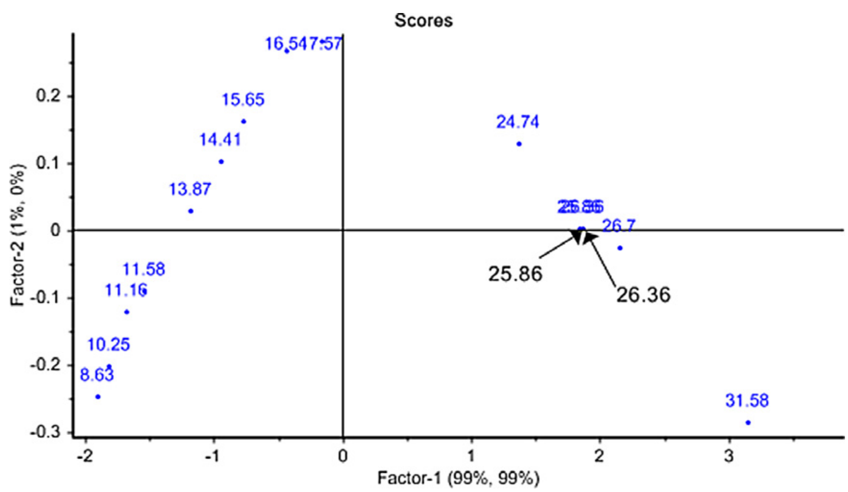

Figure 10 Scores plot.

The coefficient of correlation for calibration is 0.99689 and that for validation is 0.99567. This shows that the model gives a good fit. The RMSE for calibration is 0.6624 and for prediction is 0.56146. The difference of these two RMSE values is very less (0.10094). The R^2 values for calibration and prediction are 0.99379 and 0.99254, respectively, which shows that a good fit can be expected for future moisture predictions using this model.

Table 2 Fitness measures for the calibration set

Correlation	Slope	R^2	RMSEC	SEC	Bias
0.99689	0.99379	0.99379	0.56146	0.58266	0.00000

SEC, standard error of calibration.

Table 3 Fitness measures for the validation set

Correlation	Slope	R^2	RMSEP	SEP	Bias
0.99567	0.9907	0.99254	0.6624	0.68795	0.01537

SEP, standard error of prediction.

Comparison of fitness measures

The fitness measures for the above two cases are given in Table 4 for comparison.

As can be observed from Table 4, the RMSE for calibration as well as prediction is decreased when three electrical parameters are used for moisture prediction as compared with using capacitance alone. Similarly, R^2 for both calibration as well as prediction is increased in the latter case.

Prediction models of three different moisture levels

The experimental samples were divided into three classes depending on MC – low moisture, medium moisture and high moisture – and subsequently, the samples were reanalyzed.

The fitness measures for the calibration and validation set of all three classes of moistures are shown in Tables 5 and 6 respectively.

The prediction equations at three moisture levels are as follows:

Table 4 Fitness measures when using electrical parameters

Selection of parameters	$RMSE_{calibration}$	$RMSE_{prediction}$	$R^2_{calibration}$	$R^2_{prediction}$
Using capacitance alone	0.718233	0.861577	0.989539	0.986886
Using three parameters viz. ln C, Z and DF	0.56146	0.6624	0.99379	0.99254

DF, dissipation factor; ln C, logarithmic function of capacitance; RMSE, root mean square error; Z, impedance.

Table 5 Fitness measures for the calibration set for different moisture levels

Moisture level	Correlation	Slope	R^2	RMSEC	SEC
Low 7.96–11.58%	0.99371	0.98746	0.98746	0.16206	0.17753
Medium 13.12–17.57%	0.99274	0.98553	0.98553	0.18591	0.20365
High 19.1–31.58%	0.98763	0.9754	0.9754	0.59397	0.64156

SEC, standard error of calibration.

Table 6 Fitness measures for the validation set for different moisture levels

Moisture level	Correlation	Slope	R^2	RMSEP	SEP	Bias
Low 7.96–11.58%	0.96728	1.09481	0.93024	0.48566	0.56586	0.13719
Medium 13.12–17.57%	0.98861	0.99144	0.98409	0.23396	0.25598	-0.01136
High 19.1–31.58%	0.97799	0.95786	0.96753	0.79605	0.87861	0.09657

SEP, standard error of prediction.

$$\text{Low moisture: } 167.4009 + 0.2965327\text{DF} - 0.316643\text{Z} + 0.3143128\ln\text{C} \quad (4)$$

$$\text{Medium moisture: } 56.66774 + 0.3308124\text{DF} - 0.331288\text{Z} + 0.332093\ln\text{C} \quad (5)$$

$$\text{High moisture: } 22.38844 + 0.3342145\text{DF} - 0.3324049\text{Z} + 0.3274218\ln\text{C} \quad (6)$$

As can be observed from the fitness tables, the developed model has best performance for samples falling in the medium moisture range in validation, whereas it has best performance for low range in calibration. One of the possible reasons for this ambiguity could be that in validation, the sample set might not be falling among the population of measurement. There is a scope of developing moisture range specific prediction model using multicalibration equations. However, a tradeoff between desired measurement precision and computational complexity has to be maintained. The developed empirical equations can be useful for the development of improved technology for reliable, accurate moisture sensing in cereal grains.

Conclusion

In this paper, an accurate moisture prediction model for Indian wheat has been reported based on the variations in electrical properties. The grain samples having MC ranging from 7.1% to 34.5% were used to study the variations in various electrical properties viz. C, Z and DF in the band ranges of 1 KHz–1 MHz. A good correlation between moisture values and corresponding variations in electrical properties has been observed at 251.58 KHz frequency. The fitness measures of the developed model were compared using a single parameter, and the results were found to have improved for calibration set and comparable for validation set. The developed empirical equations can be useful for the development of improved technology for reliable, accurate moisture sensing in cereal grains. The experimental samples were divided into three classes depending on MC – low moisture, medium moisture and high moisture – and subsequently, the samples were reanalyzed to investigate range-specific precision of selected frequency. There is a scope of developing moisture range-specific prediction model using multicalibration equations.

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