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Monopole antenna technique for determining moisture content in the *Dioscorea hispida* tubers

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Abstract

This study demonstrates the determination of moisture content in *D. hispida* tuber using microwave technique. A network analyzer was used to measure the reflection coefficient of a monopole antenna inserted in *D. hispida* tuber at different percentage of moisture content. The actual moisture content of *D. hispida* tuber was determined using oven drying method. The reflection coefficient measurement was performed at operating frequency between 2 MHz and 4 GHz. The best operating frequency to model the relationship between the magnitude of reflection coefficient and moisture content in the *D. hispida* samples was found to be 0.8 GHz. The model based on measured data of sample D with a regression value of 0.9399 and 1.71% error was the most accurate model to predict moisture content in *D. hispida* tuber.

Keywords: *Dioscorea hispida*, moisture content, reflection coefficient, monopole antenna, microwave.
Abbreviations: MC – moisture content; RF – radio frequency, LAM – long antenna model, |S11|, |Γ| - magnitude of reflection coefficient, S11, Γ – reflection coefficient, *a* – radius of inner conductor, *b* – radius of outer conductor, *h* – length of inner conductor, VNA – vector network analyzer, Z – impedance, ε_r – relative permittivity, ε_o – permittivity of free space (8.85 x 10^{-12} F/m), *v* – volume, R^2 – regression value.

Introduction

Dioscorea hispida Dennst, or better known as Asiatic bitter yam or intoxicating yam, is one of the 1137 *Dioscorea* species in the *Dioscoreacea* family found throughout the world. Its distribution ranges from India and Southern China to New Guinea (Mat et al., 2010). The yam species is widely cultivated for its starchy tubers as food for millions of people especially in the rural area. Though not an important crop for the industry (Tattiyakul et al., 2006), there is a great potential for the increasingly forgotten yam in economy and scientific studies. The leaf and the tuber of *D. hispida* can be processed into bioherbicide and biopesticide products. Besides these products, the tuber of the yam species can also be processed into food products after the toxic alkaloid compounds are properly removed (Mat et al., 2010).

Moisture content (MC) is an important factor determining the storability, processing and marketability of natural products (Vesali et al., 2011; Ali et al., 2011). Drying method (Rasouli et al., 2011; Jangi et al., 2011; Tarighi et al., 2011) is a conventional method to determine moisture content of various natural products. Even though this technique is highly accurate, it is both time consuming and destructive. Therefore, there is currently great interests to develop non-destructive (or minimally-destructive) and rapid moisture detection methods suited for agricultural and food industry (Ali et al., 2011). For instance, Abbas et al. (2005), Yeow et al. (2010) and Jusoh et al. (2011) relied on open ended coaxial antenna techniques to estimate moisture content (MC) in oil palm fruit and maize kernel, respectively.

The main disadvantage of using an open ended coaxial antenna is the fact that it is only accurate for surface contact measurement of moisture bearing material. On the other hand, the monopole antenna has a long and rigid extended inner conductor which can penetrate deeper into the soft flesh of *D. hispida* sample. Thus, the measuring volume of a monopole antenna is effectively larger than an open ended coaxial antenna (Olson and Iskander, 1986), providing a more accurate assessment of moisture content distribution below surface. A monopole antenna was used by Yee et al. (2011) and Ali et al. (2011) to estimate moisture content in oil palm fruit and Hevea latex, respectively. The application of a monopole antenna to determine moisture content in *D. hispida* tuber has not been reported yet. This study aims at exploring the relationship between the reflection coefficient of a monopole antenna and moisture content in *D. hispida* tuber.

Results

Relationship between |S11| and MC in an arbitrary sample

The effective relative permittivity of a sample with varying MC can be calculated using the Kraszewski's mixing model given below:

$$\sqrt{\epsilon^*} = v_1\sqrt{\epsilon_1} + v_2\sqrt{\epsilon_2} \quad (1)$$

Where, ε_r* is the effective relative permittivity of the mixture, ε_{ri} the relative permittivity of medium and iv_i the percentage volumetric fraction of medium *i*.

The permittivity values are required as input in the calculation of reflection coefficient magnitude |S11| using long antenna model (LAM) (Wu, 1961; Olson and Iskander, 1986). As an example, if $\varepsilon_{r1} = 3$ and second medium is water, the permittivity can be calculated using the Debye model, then the results of S11 is shown in Fig. 5. Water produces multiple resonances in the |S11| plot due to its nature as a very dispersive (lossy) material. From the plot, we can observe that the relationship between |S11| and MC is not always linear. However, a linear relationship between |S11| and MC can be observed at certain frequencies. For example, the relationship between |S11| and MC is positively linear around 2.8 GHz. On the other hand, the trend between both parameters is negatively linear around 1 GHz.

Determination of optimal frequency

Variations in the measured |S11| of the monopole antenna with MC of *D. hispida* between 10 MHz and 4 GHz are shown in Fig. 6a-e. Fig. 6 shows that |S11| in *D. hispida* will also changes with the change in MC as expected. In general, at frequencies lower than 100 MHz, |S11| increases gradually as MC decreases. On the other hand, at frequencies higher than 2 GHz, |S11| increases gradually as MC increases. This trend of |S11| and MC between 100 MHZ and 2 GHz is difficult to determine by observation. Therefore, a statistical analysis was performed to precisely determine which frequency has the strongest correlation between both parameters. The correlation coefficients between measured |S11| and MC were calculated and are plotted in Fig. 7.

Discussion

Fig. 7 shows that |S11| has negative correlations with MC at frequencies lower than 0.5 GHz and positive correlations with MC at frequencies higher than 0.5 GHz, depending on sample. This implies that |S11| decreases with the increase in MC at lower frequencies and adversely at higher frequencies. Further inspection on the plots also revealed that the largest correlation coefficient, either positive or negative, for each sample occurs at different frequencies. Interestingly, all samples were found to have correlation coefficient greater than 0.9 at 0.8 GHz.

Empirical models of the relationship between |S11| and MC at 0.8 GHz were developed with simple linear regression tool. The model for each sample is plotted in Fig. 8 and Table 1 with the regression and sensitivity. The data from the table shows that the regression and sensitivity values of each empirical model vary with each sample. The models of samples C, D and E have higher R^2 values compared to models of samples A and B, indicating that it is more accurate in estimating MC in *D. hispida* tubers.

The accuracy validation of the empirical model was performed by estimating the MC based on second set of measurement. The relative error is calculated as:

$$Relative\ Error = \left|\frac{MC_{true} - MC_{predicted}}{MC_{true}}\right| \times 100\% \quad (2)$$

Where, MC_{true} is the MC of the samples determined from oven drying method, $MC_{predicted}$ is the MC of the samples determined from developed model.

The mean relative error associated with each model is shown in Tables 2a-e. From the table, relative error of samples A and B is a lot bigger than error of samples C, D and E. This is consistent with previous analysis which revealed that the empirical models for samples C, D and E have higher R^2 values than models of samples A and B. The reason for this observation is probably due to lack of uniformity of the water and other chemical compositions throughout the whole tuber. The upper part of the tuber (A and B) was actually closer to the stem of the plant than the bottom part (D and E). Therefore, it is possible that the upper part of the tuber might have a different composition that the lower parts.

Data calculated with equation (2) suggests that a freshly harvested *D. hispida* tuber contains between 70% and 80% of MC. This range is consistent with the MC of yams (*Dioscroea* spp.) which was reported to have 50% to 80% (Degras, 1993; Bhandari et al., 2003); water yam tuber (*Dioscorea alata*) 72% (Baah, 2009); sweet potato tuber 65.6% to 80.7% (Brinley et al., 2008; Batson and Hogan, 1949), and potato tuber 71.8% to 83.3% (Nelson, 2005; Hansen et al., 2010). Although the monopole antenna described in Ali et al. (2011) was able to measure 20% to 80% MC in latex, it should be noted that the antenna was a blade monopole sensor suitable for liquid samples only.

Materials and methods

Transmission line and antenna theory

The reflection coefficient represents the mismatch between antenna and transmission line impedances as shown in Fig. 1. The parameter is defined in Pozar (2004) as:

$$S11(\omega) = \frac{V^-}{V^+} = \frac{Z_{load} - Z_o}{Z_{load} + Z_o} \quad (3)$$

Where, S11 (ω) reflection coefficient at port 1
V^- is the reflected power
V^+ is the incidence power
Z_o is the characteristic impedance of the low loss cable
Z_{load} is the characteristic impedance of the antenna

The S11 is a function of operating frequency according to King et al. (1973), Burdette et al. (1980), Olson and Iskander (1986) and Misra (1988). The length of the inner conductor *h*, the radius of the inner conductor *a*, and the permittivity of the medium surrounding the antenna are depicted in Fig. 2.

Since the length and radius of the antenna are constant (*h* = 1.749 cm, *a* = 0.64), the impedance of the antenna depends on the frequency and the dielectric properties of the medium surrounding the antenna with an assumption that the medium is homogeneous. Air has a constant permittivity of 1 for all frequency. On the other hand, water has a complex dielectric

Table 1. Regression value and sensitivity of each empirical model describing the relationship between |S11| and MC at 0.8 GHz.

Sample	Equation	Regression values, R^2	Sensitivity (%)
A	|S11| = 2.5619*(MC%) - 1.1501	0.8866	0.0256
B	|S11| = 2.6694*(MC%) - 1.2986	0.8727	0.0267
C	|S11| = 2.473*(MC%) - 1.2307	0.9096	0.0247
D	|S11| = 2.5711*(MC%) - 1.3597	0.9399	0.0257
E	|S11| = 2.2589*(MC%) - 1.1387	0.9116	0.0226

Table 2. The validation of empirical model for each sample. The predicted MC is obtained from empirical model while the actual MC is obtained the second set of measurement. Relative error is calculated from equation (2). (a) Sample A, (b) Sample B, (c) Sample C, (d) Sample D, (e) Sample E.

Magnitude	Predicted MC	Actual MC	Relative Error
0.7287	71.5%	71.9%	0.56%
0.7023	70.6%	68.0%	3.82%
0.5926	67.2%	63.9%	5.16%
0.4885	64.0%	58.3%	9.78%
0. 1864	54.7%	52.2%	4.79%
0.1739	54.3%	54.8%	0.91%
0.1682	54.1%	60.2%	10.13%
Average relative error for sample A			5.02%

Magnitude	Predicted MC	Actual MC	Relative Error
0.6294	70.8%	71.3%	0.70%
0.4672	65.5%	67.9%	3.53%
0.4393	64.6%	62.5%	3.36%
0.4089	63.6%	61.0%	4.26%
0.3592	62.0%	56.5%	9.73%
0.3348	61.2%	58.4%	4.79%
0.2730	59.2%	65.5%	9.62%
Average relative error for sample B			5.14%

Magnitude	Predicted MC	Actual MC	Relative Error
0.6447	74.5%	74.78%	0.37%
0.5970	72.9%	71.66%	1.73%
0.4981	69.6%	68.38%	1.78%
0.3577	65.0%	64.36%	0.99%
0.2711	62.1%	65.77%	5.58%
0.2595	61.7%	60.04%	2.76%
0.2392	61.0%	61.78%	1.26%
Average relative error for sample C			2.07%

Magnitude	Predicted MC	Actual MC	Relative Error
0.6493	77.6%	74.96%	3.52%
0.5898	75.4%	76.58%	1.54%
0.4758	71.2%	68.08%	4.58%
0.4556	70.5%	71.88%	1.91%
0.2977	64.7%	65.73%	1.57%
0.2265	62.1%	63.95%	2.89%
0.1876	60.7%	61.48%	1.26%
Average relative error for sample D			2.47%

Magnitude	Predicted MC	Actual MC	Relative Error
0.6230	77.0%	74.61%	3.20%
0.6089	76.4%	77.18%	1.01%
0.4035	68.2%	71.41%	4.50%
0.3424	65.7%	68.73%	4.41%
0.3052	64.2%	66.52%	3.49%
0.2787	63.1%	62.10%	1.61%
0.1965	59.8%	59.30%	0.84%
Average relative error for sample E			2.72%

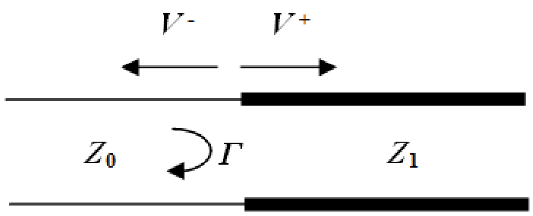

Fig 1. Reflection coefficient *Γ* is the ratio of the reflected power V^- to the incidence power V^+ at the junction of two transmission lines with different characteristic impedance *Z*.

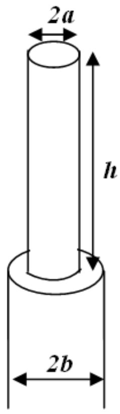

Fig 2. The simple diagram of the monopole antenna with length of the extended inner conductor *h*, radius of the inner conductor *a* and outer conductor *b*.

Fig 3. Samples preparation of *D. hispida* tuber labeled as A, B, C, D and E (a) before cutting, (b) after cutting.

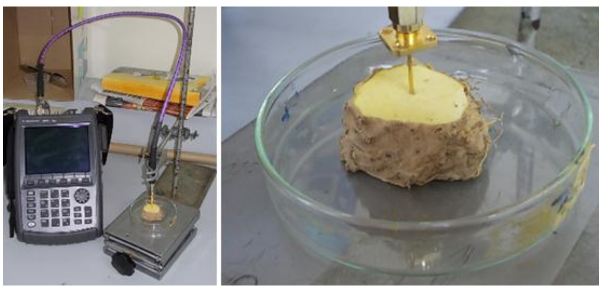

Fig 4. Experimental setup, (a) VNA, low loss cable, monopole antenna and sample holder, (b) monopole antenna partially inserted into *D. hispida* sample.

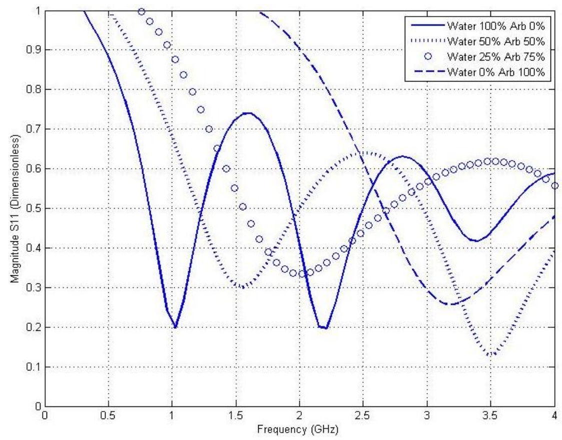

Fig 5. The theoretical |S11| of a monopole antenna (h = 1.3 cm, a =) inserted in a theoretical sample ($\varepsilon = 3\varepsilon_o$) with varying MC calculated using equation (1), equation (3) and LAM.

property that can be represented by a Debye type relaxation given below as (Kaatze, 2005). Water molecule orients and polarizes specifically to the direction of electric field in microwave region due to its molecular structure and bonding (Kaatze, 2005). Because of high variation in dielectric constant and loss factor across microwave region, water is deemed as a highly dissipative medium. Due to this nature, microwave is a very useful method to detect moisture content with high sensitivity to detect an even small amount of water (Kraszewski, 2005).

Samples preparation

The freshly harvested tubers of *D. Hispida* were provided by the Faculty of Agriculture and Biotechnology, Universiti of Sultan Zainal Abidin (UniSZA).

The skin of *D. hispida* tuber has a bright brown appearance and covered with fibrous rootlets (Fig. 3a). The fibrous rootlets were cut and then tuber was brushed thoroughly to remove dirt, dust and soil that may be present on the skin of the tuber. The whole tuber of *D. hispida* was cut evenly into five samples of two centimeters thick namely A, B, C, D, and E as depicted in Fig. 3b.

The samples were cut into five parts to speed up the drying process and determine which part of tuber is most accurate to predict MC in *D.hHispida* tuber. Before drying, the raw flesh of the tuber yields has a white to bright lemon-yellow appearance. Each sample was weighted separately using a Shimadzu Y220 electronic weight balance.

Measurement setup

The measurements of MC in the samples were carried out at the Department of Physics, Faculty of Science, Universiti Putra Malaysia. As depicted in Fig. 4, the measurement setup consisted of an Agilent FieldFox Network Analyzer (NA) N9912A, a monopole sensor fabricated from a simple and low cost RF stub connector and a low-loss coaxial cable.

The frequency range was set at 2 MHz through 4 GHz. The calibration at the open end of the cable had to be performed before the antenna was mounted to correct for any loss in the cable. The calibration involved only one port because only the reflection coefficients were measured at port 1. The calibration kit intended for this process consisted of only a

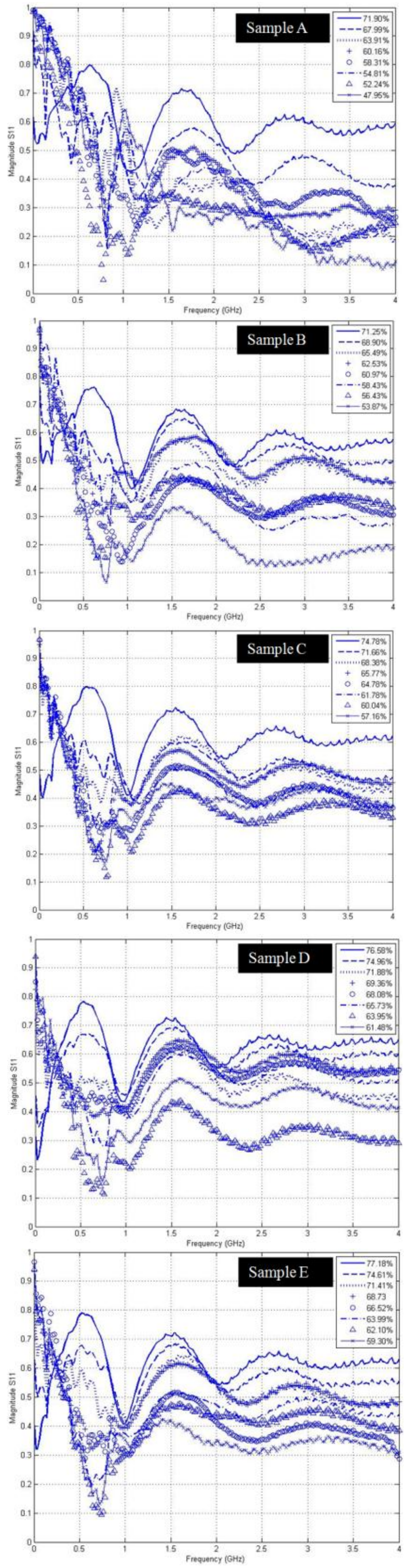

Fig 6. The legend shows the different MC of the samples. As MC varied, the |S11| for each sample also changed. The relationship between |S11| and MC can be modeled using data presented in these figures. (a) The plot of |S11| against frequency for Sample A, (b) The plot of |S11| against frequency for Sample B, (c) The plot of |S11| against frequency for Sample C, (d) The plot of |S11| against frequency for Sample D, (e) The plot of |S11| against frequency for Sample E.

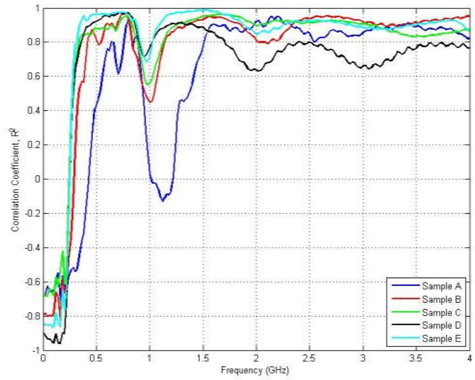

Fig 7. Coefficient of correlation between the |S11| and MC for each *D. hispida* sample based on plots in Fig. 6. The plot suggests that all samples yields high positive correlation at 0.8 GHz.

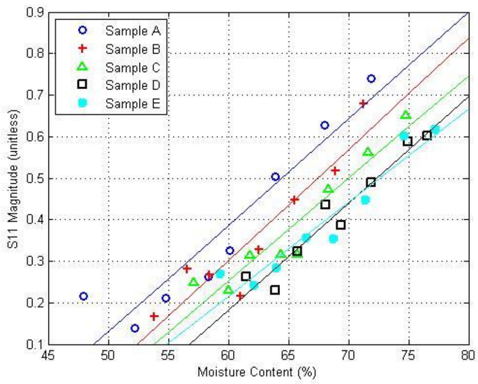

Fig 8. Variations in |S11| against MC for each plot at 0.8 GHz for all samples taken from measured data presented in Fig. 6. The symbols represent the measured data while the straight line represent the empirical model developed based on the measured data. The equation, regression value and sensitivity of each model are given in Table 1.

Hawlett Packard HP902C-6003 broadband 50 Ohm load. After the calibration was completed, the antenna was connected to the end of the cable and measured in the air. Then, the antenna was inserted into sample A and the sample was measured. This step was repeated for other samples before drying.

Moisture content measurements

The standard oven drying methods for determining true MC of tuberous crops are given in Agrawal (1993). However, the gradual changes of MC in the sample cannot be determined with this method. Therefore, we proposed a modified method to obtain gradual changes of MC in the *D. hispida* samples. The samples were first heated at 70°C for 3 hours. Then, the samples were taken out and left to cool down at room temperature for at least 90 minutes. After the S11 measurements were made, the samples were heated again at 70°C for another 3 hours. This process was repeated until no significant change in MC is detected.
Two sets of measurement were made; one for developing prediction models and another for validating the models. Every measurement was taken at different point or position on the samples because every measurement requires the

antenna to penetrate the flesh of the samples; thus, leaving a small hole on the surface of the samples. After that, the samples were dried at 100°C for 6 hours to speed up the drying process and the weights of the samples were again measured. This process was repeated until the weights reading became consistent. The wet basis MC of a material is defined as (Kraszewski, 2005):

$$MC = \frac{m_{wet} - m_{dry}}{m_{wet}} \times 100\% \tag{4}$$

Where, m_{wet} and m_{dry} is the mass of the samples before and after drying, respectively.

Conclusion

This study successfully demonstrated the determination of moisture content in the *D. hispida* tuber between 45% and 80% using a monopole antenna. Five different empirical models were developed and validated based on the magnitude of the reflection coefficient of a monopole antenna inserted in the *D. hispida* tuber. The recommended operating frequency for the models was 0.8GHz. The lower part of the tuber is recommended for measurement of moisture content. This technique is minimally-destructive, simple to use, and low cost which makes it a potentially useful tool in agriculture and food industries. Furthermore, this technique is suitable not only for detecting moisture content in *D. hispida* but also other tuberous crops such as potato, sweet potato, common yam and *D. alata*. However, this will require a new set of measurement data and empirical models.

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