Sains Malaysiana 48(5)(2019): 1111–1119
http://dx.doi.org/10.17576/jsm-2019-4805-20

Subminiature Panel (SMA-P) Coaxial Sensor for the Determination of Moisture Content of Mango cv. Chok Anan

(Penderia Sepaksi Panel Subminiatur (SMA-P) untuk Penentuan Kandungan Lembapan Mangga cv. Chok Anan)

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ABSTRACT

The research describes the development of a simple, cheap and efficient open-ended coaxial sensor for the determination of moisture content of Chok Anan mango during fruit ripening from week 5 to week 17. The sensor was a modification of a standard subminiature panel (SMA-P). The finite element method was used to calculate the numerical values of the reflection coefficient. The reflection coefficient of the sensor was measured using a Microwave Network Analyzer in the frequency range from 1 to 4 GHz. The actual moisture content was obtained using standard oven drying method. A calibration equation was obtained to predict moisture content from the measured reflection coefficient at 1 GHz with accuracy within 1.5%. The results indicate that the amount of m.c. in Chok Anan mango can be determined with excellent accuracy using a SMA-P coaxial sensor as an OEC sensor.

Keywords: Finite element method; moisture content; open-ended coaxial sensor; reflection coefficient; SMA-P

ABSTRAK

Kajian ini menerangkan pembangunan penderia sepaksi hujung terbuka yang mudah, murah dan cekap dalam menentukan kandungan lembapan mangga Chok Anan sepanjang kematangan buah dari minggu ke 5 hingga minggu 17. Penderia tersebut adalah pengubahsuaian daripada panel subminiatur (SMA-P) piawai. Kaedah Unsur Terhingga digunakan untuk menghitung nilai berangka pekali pantulan. Pekali pantulan untuk penderia diukur dengan menggunakan Microwave Network Analyzer *dalam julat frekuensi daripada 1 hingga 4 GHz. Kandungan lembapan sebenar diperoleh menggunakan kaedah piawai pengeringan ketuhar. Persamaan penentukuran diperoleh untuk meramalkan kandungan lembapan daripada pengukuran pekali pantulan pada 1 GHz dengan ketepatan yang diperoleh adalah 1.5%. Keputusan menunjukkan bahawa jumlah m.c. dalam mangga Chok Anan boleh ditentukan dengan ketepatan yang sangat baik menggunakan penderia sepaksi SMA-P sebagai penderia OEC.*

Kata kunci: Kaedah unsur terhingga; kandungan lembapan; penderia sepaksi hujung-terbuka; pekali refleksi; SMA-P

INTRODUCTION

Mango (*Mangifera indica* L.) belongs to Anacardiaceae family with 60 genera (Abidin 1991), one of the popular tropical fruits. Mango is listed as 15 types of fruit commodities in National Agro-Food Policy (2011-2020) with estimated high export value of RM4255.952 million in 2017 (DOA 2017). The external properties such as size, color, shape and defect are commonly used for the quality evaluation in mango. However, these properties may not accurately correlate to the internal quality of the fruit such as sugar content, acidity, firmness and internal breakdowns (Soltani et al. 2011).

According to Ragni et al. (2006), the measurement of moisture content (m.c.) remains the prime interest for the quality evaluation of agricultural products. Many techniques have been reported such as Karl Fischer titration (Gallina et al. 2010), optical (Norimi et al. 2012) and standard oven drying (Ahn et al. 2014) that had been used previously for m.c. determination in agricultural products.

Microwave technique remains among the most important technique in m.c. measurement. According to a survey, over thirty companies have been involved in the manufacturing and applying microwave-based moisture measurement technique especially in agriculture products (Kaatze et al. 2005). In recent years, numerous microwave-based techniques have been vigorously developed for m.c. determination in agricultural products (Kupfer 2005). The m.c. can be determined by a variety of methods, yet, obtaining a fast and accurate data is commonly a challenge, especially if the required method is non-destructive. To date, the dielectric technique is more suitable to determine the m.c. of crops including mango. It is appropriate for food and agriculture applications and highly desired due to its advantages of the rapidity, accuracy, non-destructive and has wide sensing area features. Besides, the dielectric properties of a moist material highly depend on its amount of m.c. (Kandala et al. 2007). The higher the water dipole molecule mobility and ionic conductivity indicate the higher m.c. in the sample.

The open-ended coaxial (OEC) sensor is commonly used in the dielectric measurement techniques and is widely implemented in various industrial and scientific applications involving fruits and vegetables (Schubert & Regier 2005; Wang et al. 2003), pharmaceutical industry (Auriemma et al. 2011; Nurjaya et al. 2005; Wong et al. 2002), and biological tissues (Adair & Peterson 2002; Metaxas & Meredith 1983). In this method, the reflection coefficient is measured when the sample is placed against an open-ended coaxial (OEC) line. The equivalent admittance model of the coaxial sensor is then used to calculate the complex permittivity of the material (Abbas et al. 2005). A coaxial line includes the inner and outer radii. It is filled with a lossless homogeneous dielectric with a relative permittivity which is terminated in the plane z=0 into a flat metallic flange extending theoretically to infinity in the transverse direction (Poumaropoulos & Misra 1993). The material terminating the aperture is assumed to be homogeneous, isotropic, linear, and nonmagnetic, of complex permittivity extending to infinity.

Basically an OEC sensor has been reported by many researchers as a non-destructive sensor for measuring m.c. (Abbas et al. 2005) and complex permittivity (Grant et al. 1989; Marsland & Evans 1987) of materials. The Agilent HP85070B/E is a commercial dielectric probe based on OEC sensor. This industry standard probe is used for measuring the permittivity of liquid and semi-liquid materials. However, this probe was also used in past studies to measure permittivity of fruits and rhizomes (Nelson et al. 1994). Since the permittivity of a moist material depends on the amount of water contained in the material, this probe can also be used to indirectly determine m.c. of agricultural products such as latex (Ansarudin et al. 2012) and palm oil (Yeow et al. 2010). Measuring permittivity with Agilent HP85070B/E is easy, simple and fast since it comes with its own calibration kit and software. However, this dielectric probe is very expensive. Therefore, this work focuses on the application of subminiature panel (SMA-P) coaxial sensor which can be an alternative sensor to the expensive industrial OEC sensor. This research presents the application SMA-P coaxial sensor as a non-destructive sensor for the determination of m.c. in Chok Anan mango based on magnitude of reflection coefficient measurements. In addition, finite element method (FEM) was also used to calculate the reflection coefficient of the OEC sensor in the operating frequency between 1 and 4 GHz.

Materials and Methods

Sample Preparation

The randomization design was used in this study in which 55 fresh Chok Anan mango samples were picked randomly from mango plot (five randomly selected mango trees) at MARDI Kundang, Selangor, Malaysia. All the samples were washed and sliced into cubicle shape with a size of 2.0 cm × 3.0 cm and 1.5 cm (length × width × height) without removing the skin.

Moisture Content Measurement

The microwave oven-drying method was used to determine the actual m.c. of mango. This method uses the official AOAC method (AOAC 2000; Nielsen 2010) with two minor modifications on time and power setting. Each sample was dried for 20 min with 550W microwave power to fulfill the minimum requirement for water (Michael et al. 1991). The dried samples were cooled at room temperature of 25°C before being weighed again. Prior to the drying procedure, each part was weighed separately using a Shimadzu Y220 electronic weight balance (Shimadzu Corporation, Japan) with 0.1 mg precision. The process was repeated until no significant change in m.c. was detected. The process was repeated until a constant mass ± 0.5 mg was obtained for each sample (Yahaya et al. 2014a).

Development of SMA-P Coaxial Sensor

The SMA-P coaxial sensor used in this work was a modification of a commercial standard SMA stub contact panel manufactured by Tyco Electronics as shown in 1(a). The square flange (12.7 mm × 12.7 mm) served as the ground plane. The input port was a SMA female type with insulation material made of polytetrafluroethylene (PTFE). The protruding inner conductor of the stub was cut, machined and polished to a flat surface as shown in Figure 1(b).

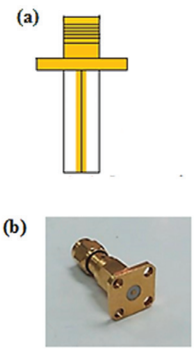


FIGURE 1. (a) The diagram of commercial standard SMA stub contact panel and (b) SMA-P coaxial sensor

Measurement of Reflection Coefficient Magnitude

The measurement setup consisted of a N9912A Keysight FieldFox Network Analyzer (NA) (Keysight Technologies, Inc., California) and SMA-P coaxial sensor. This measurement was carried out at the Radio Frequency and Microwave Laboratory, Department of Physics, Faculty of Science, Universiti Putra Malaysia. The operating frequency of the measurement was set from 1 to 4 GHz. The calibration has to be implemented at the open end of the cable to free from any loss in the cable prior the mounting of SMA-P coaxial sensor. One port calibration was needed in this process since only the reflection coefficients were measured at port 1. The calibration kit used for this process is a Hewlett Packard HP902C-6003 broadband 50

Ω load. The magnitude of the reflection coefficient was measured by connecting the SMA-P coaxial sensor to the end of the cable and measured the air and water prior the samples. Data were analyzed using analysis of variance (ANOVA) (SAS Institute 1989).

FINITE ELEMENT METHOD (FEM) USING COMSOL

The required parameters in COMSOL, such as the input values of the dielectric constant and loss factor for the samples of different percentages of m.c. were obtained from the Agilent Dielectric Probe Kit 85070E. The calculation of the reflection coefficient, Γ in FEM using COMSOL can be accomplished by defining (Comsol Multiphysics 2006):

$$\Gamma = \frac{\sqrt{P_{ref}}}{\sqrt{P_{in}}} \tag{1}$$

where P_{ref}, is the reflected power; and P_{in} is the input power.

Given that

$$P_{ref} = \sqrt{P_{in}} - \sqrt{P_{dissipated}} \tag{2}$$

$$P_{in} = \frac{1}{2}\sqrt{\frac{\varepsilon_{coax}}{Z_o} \times \frac{(E_{r1} \times jE_{r1})}{r^2}} \tag{3}$$

where r is the radius of the port; ε_{coax} is the permittivity of coaxial cable (V/m); Z_S is the input impedance of the loaded sensor; V is the peak value of the source ; and Z_o is the 50 Ω characteristic impedance of the cable.

$P_{dissipated}$ is the dissipated power that can be define as

$$P_{dissipated} = \frac{V^2}{2|Z_o + Z_S|^2} \mathrm{Real}(Z_s) \tag{4}$$

There are 13 boundaries; two boundaries for port and axial symmetry, respectively, three boundaries represent the continuity, another three represents matched boundary for sample, and the rest represent perfect electric conductors on the SMA-P coaxial sensor. The design model of OEC sensor using COMSOL software in two dimensions' axial symmetry is shown in Figure 2. Generally, the higher the numbers of FEM mesh elements produce more accurate computational result using FEM (Yahaya et al. 2014b). The calculated magnitude of reflection coefficient, |Γ| were using extra fine mesh elements with 2916 elements.

RESULTS AND DISCUSSION

|Γ| OF CHOK ANAN MANGO AT DIFFERENT PERCENTAGE OF MOISTURE CONTENT

The measurement results for the variation in |Γ| of Chok Anan mango with operating frequency from 1 to 4 GHz at various percentages of m.c. from 72.7 to 88.1 % are illustrated in Figure 3. Water molecule orients and polarizes specifically to the direction of electric field in microwave region due to its molecular structure and bonding. The higher the m.c. in the samples, hence the higher are the values of |Γ| for the mangoes. These are expected as the higher the m.c., the higher were the values of the ε' and thus the higher were the magnitude of |Γ| according to the impedance matching and mixture theory equations (Jha et al. 2011). It should be noted that ε' decreased as the frequency increased (Sosa-Morales et al. 2009; Suhaime et al. 2018). Thus from impedance matching theory, |Γ| values also decreased as the frequency increased for all samples. The |Γ| values at 1 GHz were between 0.89 and 0.94 whilst the corresponding range was larger at 4 GHz from 0.67 to 0.85. The |Γ| range was initially smaller at 1 GHz before it diverged to a larger extent after a critical frequency as the frequency increased towards 4 GHz. This was due to the effect of two mechanisms which were bound water relaxation (lower frequency) and free water relaxation (higher frequency). |Γ| for all the samples decreased almost exponentially with frequency. However, the higher

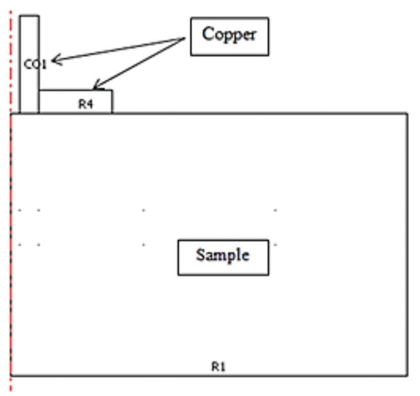


FIGURE 2. Two dimensional axis symmetry of SMA-P coaxial sensor loaded with sample using COMSOL software

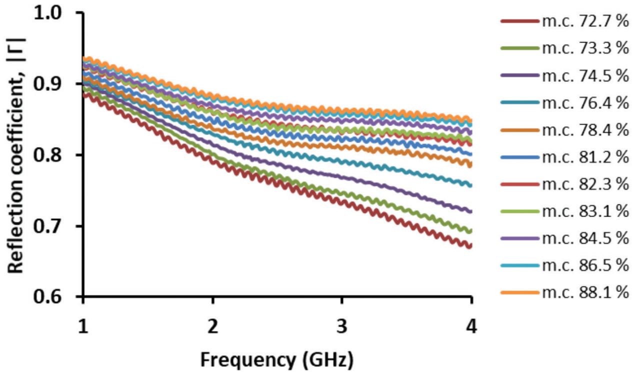


FIGURE 3. Variation in |Γ| of Chok Anan mango with frequency at eleven values of m.c.

the amount of m.c. in the samples hence the higher the tendency for |Γ| to follow the |Γ| profile for water as shown in Figure 4(a).

COMPARISON BETWEEN MEASURED AND CALCULATED |Γ| AT DIFFERENT PERCENTAGE OF MOISTURE CONTENT OF CHOK ANAN MANGO

The comparison between measured and calculated |Γ| for the standard materials such as water and air are illustrated in Figure 4. The calculated results were obtained from the finite element method (FEM). Close agreements were obtained with mean relative errors of 1.4 and 1.2% for water and air, respectively, when using extra fine meshes with 2916 elements. The comparison between measured and calculated |Γ| for the mango samples with m.c. from 72.7 to 88.1 % are shown in Figure 5. The |Γ| has the same profile as the calculated |Γ| profile where the values decreased as the frequency increased (King et al. 1973).

The permittivity inputs obtained from the Keysight OEC probe was required for the calculation of |Γ| when using COMSOL. The simulation results show very good agreement between the calculated and measured results especially at lower operating frequencies (5) coinciding with the critical frequencies of the ε" described previously (Suhaime et al. 2018). At the critical frequency, the ε" increased where water molecules changed from the bound state to the free state which was not taken account in the Keysight probe software.

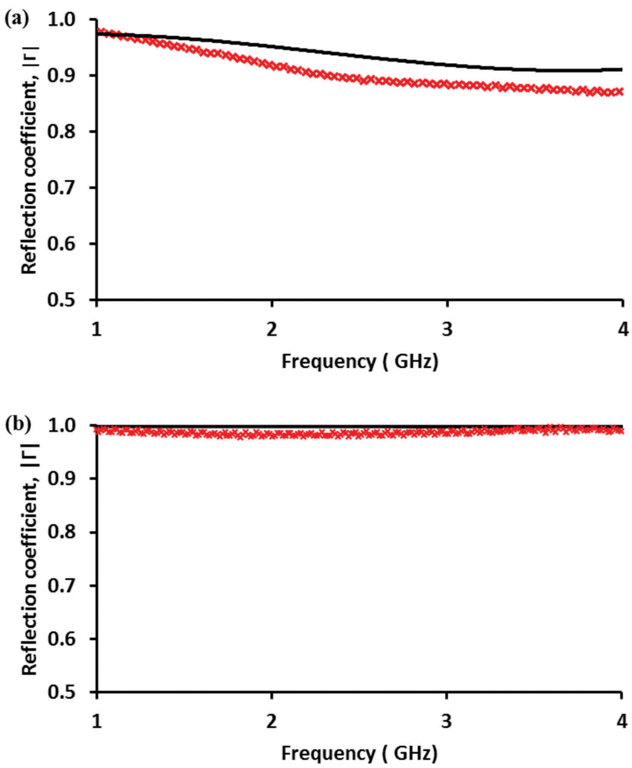
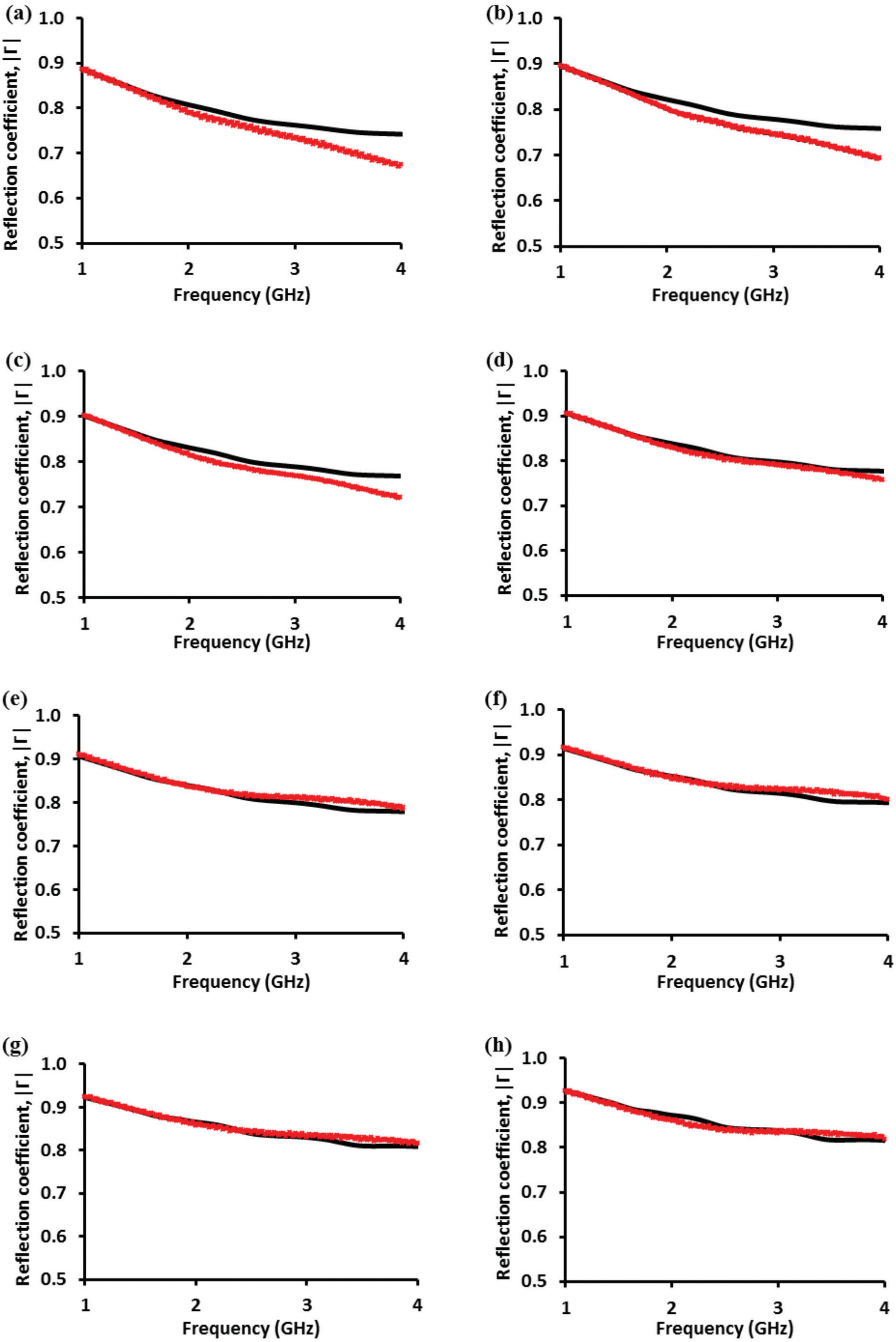


FIGURE 4. Comparison between measured (xxxx) and calculated (▬) |Γ| of standard materials (a) water and (b) air using SMA-P coaxial sensor


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Reflection coefficient, |Γ|
Frequency (GHz)
1.0
0.9
0.8
0.7
0.6
0.5
1
2
3
4

continue

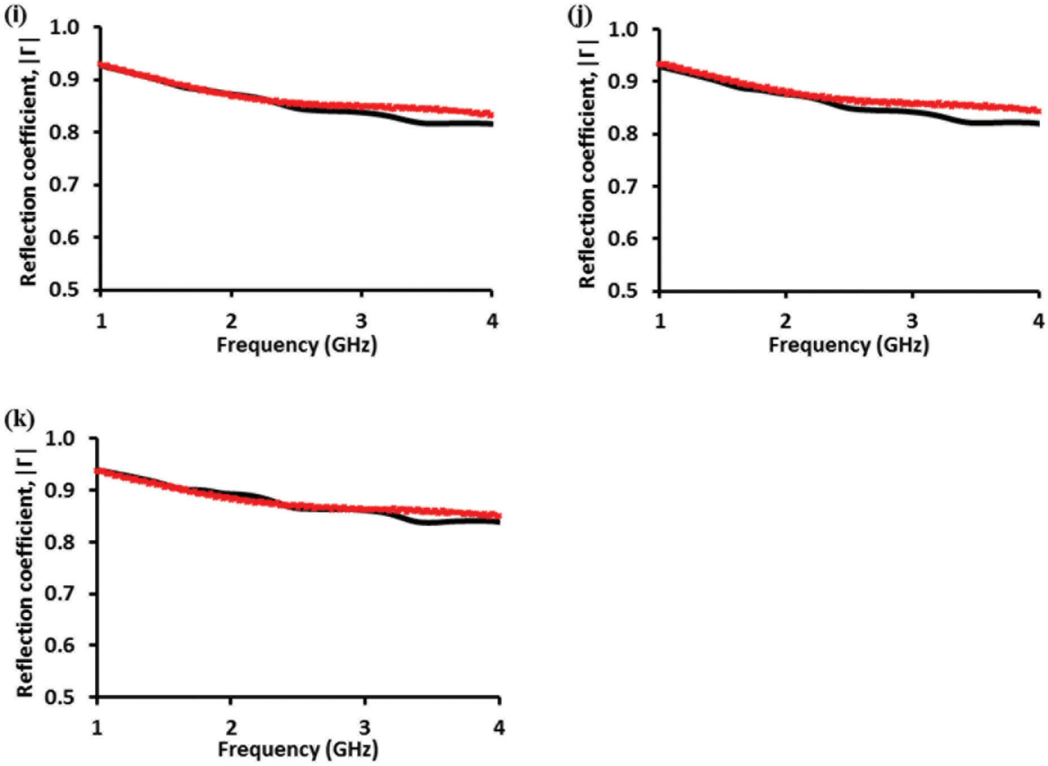


FIGURE 5. Comparison between measured (xxxx) and calculated (▬) |Γ| with frequency for various percentages of m.c. (a) 72.7%, (b) 73.3%, (c) 74.5%, (d) 76.4%, (e) 78.4%, (f) 81.2%, (g) 82.3%, (h) 83.1%, (i) 84.5%, (j) 86.5%, and (k) 88.1%

The mean relative error between the measured and calculated |Γ| for the whole operating frequency from 1 to 4 GHz was 1.5 %. The errors for all the samples are listed in Table 1. Higher errors were found from samples with lower m.c. due to inaccurate values of permittivity predicted by the Keysight probe software for moist materials. The Keysight probe software utilizes a Cole-Cole model to predict permittivity of samples. However the Cole-Cole model is designed for permittivity calculation of liquids, not for semi-solid samples.

TABLE 1. Relative error between measured and calculated |Γ|

m.c. (%)	Relative error (%)
72.7	3.2
73.3	3.3
74.5	2.2
76.4	0.8
78.4	0.9
81.2	0.8
82.3	0.7
83.1	0.8
84.5	1.1
86.5	1.5
88.1	0.8
Mean relative error (%)	1.5

CORRELATION BETWEEN MEASURED AND CALCULATED |Γ| WITH MOISTURE CONTENT

The impedance of the SMA-P coaxial sensor depends on both the frequency and the dielectric properties of the sample surrounding the sensor (Zainuddin et al. 2013). The impedance mismatch at the interface between the probe and sample determines the values of |Γ|. The higher the amount of m.c. in the samples will result in higher value of the ε' (Tang 2005). These in turn will increase the impedance mismatch and thus |Γ| values. The variation in |Γ| with m.c. for several selected frequencies are shown in Figure 6. The values of |Γ| increased exponentially with m.c. The calculated |Γ| shows good agreement with the measured values at 1 GHz. As the frequency increased, the higher was the deviation between the measured and calculated |Γ| and vice versa for m.c. This is probably due to the effect of the non-uniformity distribution of moisture inside the samples due to the transition from bound to free water (Kupfer 2005; Serdyuk 2008) that has not taken into account by the Keysight probe software as described in the previous paragraphs.

The relationship between measured |Γ| with m.c. as well as R^2 values are tabulated in Table 2. Higher R^2 values were obtained at higher operating frequencies for measured |Γ|. Higher R^2 means higher correlation between |Γ| with m.c. and it was proved based on the analysis of variance (ANOVA) in Table 3. It shows that the lowest p-value = 9.62×10^{-21} was found at 4 GHz compared to 1 GHz (p-value = 9.88×10^{-21}), 2 GHz (p-value = 9.73×10^{-21}) and 3 GHz

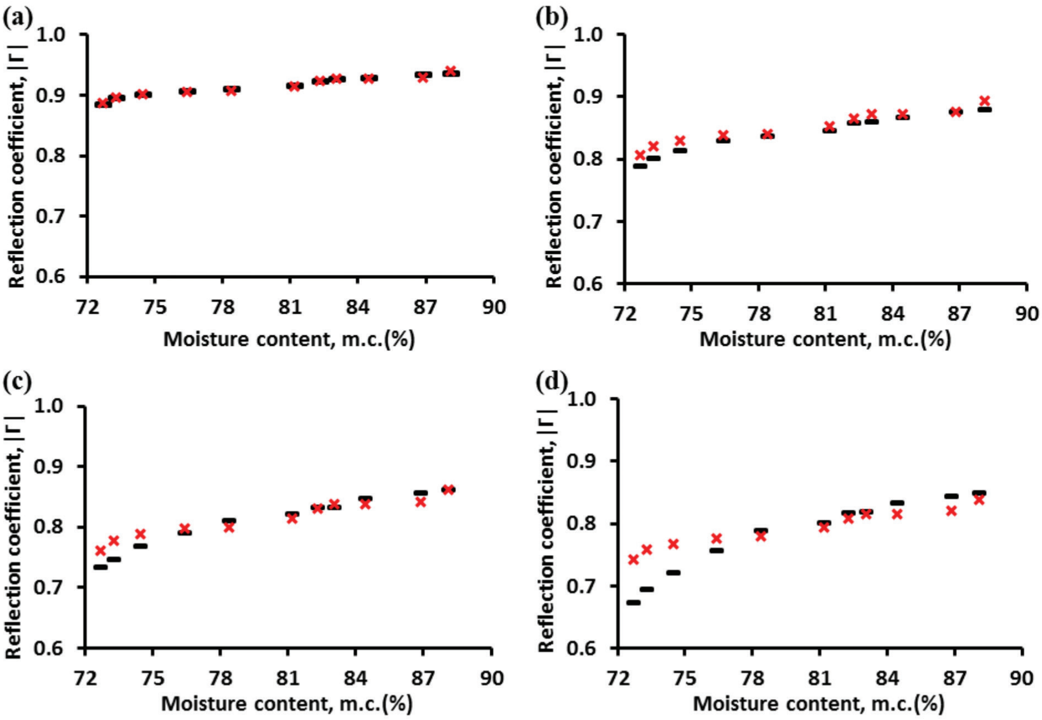


FIGURE 6. Comparison between calculated (x)and measured (▬) |Γ| with various percentage of m.c. at selected frequencies: (a) 1 GHz, (b) 2 GHz, (c) 3 GHz, and (d) 4 GHz

TABLE 2. Relationship between measured |Γ| and m.c.

Frequency (GHz)	Measured	R^2
1	$\|\Gamma\| = -8x10^{-5}m.c.^2 + 0.0154m.c. + 0.1797$	0.975
2	$\|\Gamma\| = -0.0002m.c.^2 + 0.0338m.c. - 0.7299$	0.984
3	$\|\Gamma\| = -0.0004m.c.^2 + 0.0660m.c. - 2.1381$	0.988
4	$\|\Gamma\| = -0.0007m.c.^2 + 0.1157m.c. - 4.2708$	0.989

TABLE 3. Statistical analysis using ANOVA at selected frequencies: 1, 2, 3 and 4 GHz

	ANOVA						
Frequency (GHz)	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
	Between Groups	31950.25	1	31950.25	2476.157	9.88E-21	4.413873
1	Within Groups	232.2568	18	12.90316			
	Total	32182.5	19				
	Between Groups	32007.57	1	32007.57	2480.553	9.73E-21	4.413873
2	Within Groups	232.2613	18	12.9034			
	Total	32239.83	19				
	Between Groups	32031.27	1	32031.27	2482.318	9.66E-21	4.413873
3	Within Groups	232.268	18	12.90378			
	Total	32263.54	19				
	Between Groups	32050.93	1	32050.93	2483.714	9.62E-21	4.413873
4	Within Groups	232.2799	18	12.90444			
	Total	32283.21	19				

(p-value = 9.66×10^{-21}). However, it should be noted that higher correlation does not guarantee high accuracy. The accuracy can only be obtained by comparing the predicted and measured values using standard methods.

TABLE 4. Calibration equation models relating m.c. to |Γ|

Frequency (GHz)	m.c.	R^2	Mean relative error (%)
1	m.c.= 3273.80|Γ|^2 – 5655.4|Γ| + 2513.10	0.985	1.5
2	m.c.= 1094.90|Γ|^2 – 1655.3|Γ| – 696.81	0.992	1.8
3	m.c.= 739.95|Γ|^2 – 1061.2|Γ| – 453.07	0.994	2.5
4	m.c.= 499.09|Γ|^2 – 676.8|Γ| – 302.50	0.993	4.1

The equation in Table 2 can be used to determine the measured |Γ| for a given value of m.c. Conversely, the measured |Γ| using SMA-P coaxial sensor can be used to predict m.c. in the mango samples by exchanging the calculated and measured |Γ| with m.c. in the x- and y-graph.

CALIBRATION EQUATIONS TO PREDICT MOISTURE CONTENT

Calibration equations were obtained from the relationship between measured |Γ| and m.c. for the frequency 1, 2, 3 and 4 GHz. The accuracy of the calibration equations was determined by calculating the errors between the actual m.c. obtained from microwave oven drying method and predicted m.c. obtained using |Γ| measurements. The most accurate equation to predict m.c. in Chok Anan mango was found at 1 GHz as shows in Table 4. The highest accuracy of the predicted m.c. was 1.5 % of mean relative error. Similar accurate measurement results at the vicinity of 1 GHz have been reported for other types of moist materials (Kupfer 2005; Nyfors & Vainikainen 1989). Yet, the exact causes are currently unknown, though several theories have been postulated, such as the difference between free and bound water effect is located in the frequency domain from 100 MHz to 1 GHz (Pyper et al. 1985).

CONCLUSION

The SMA-P coaxial sensor was used successfully for the determination of the m.c. with the accuracy of 1.5 %. The results indicated the amount of m.c. in Chok Anan mango can be determined with excellent accuracy using a SMA-P coaxial sensor as an OEC sensor. The major benefit of this sensor over the other alternative techniques is the ability to provide a measurement method that is simultaneously very quick, simple, cheap and non-destructive.

ACKNOWLEDGEMENTS

The research was supported by the Ministry of Higher Education, Malaysia (MOHE) (FRGS/1/2015/TK02/MOA/02/1). The authors would like to express utmost gratitude to Malaysian Agricultural Research and Development Institute (MARDI) and Universiti Putra Malaysia (UPM) for the use of facilities for the research. The gratitude is also extended to MARDI Kundang for the mango samples and staff assistance during the sampling process. Finally, thanks to Fadhilnor Abdullah (MARDI Perlis) for his assistance with data interpretation.

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Received: 30 November 2018
Accepted: 11 March 2019