ASM Sc. J., 13, Special Issue 4, 2020 for NCAFM2018, 9-19

Open-ended Coaxial Sensor for the Assessment of Physicochemical and Dielectric Properties of Watermelon

M. Sairi[1*], N. Suhaime[2], Z. Abbas[2], N.B. Mohamed Nafis[2], A.S. Mhd Adnan[1], A.R. Shamsulkamal[1] and Z. Othman[3]

[1] *Engineering Research Centre, Malaysian Agricultural Research and Development Institute (MARDI), MARDI Headquarters, Persiaran MARDI-UPM, 43400 Serdang, Selangor, Malaysia*

[2] *Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

[3] *Industrial Crop Research Center, Malaysian Agricultural Research and Development Institute (MARDI), MARDI Headquarters, Persiaran MARDI-UPM, 43400 Serdang, Selangor, Malaysia*

A dielectric based measurement system was used in the assessment of watermelon internal quality, focusing on maturity stage. This technique is based on measurement at watermelon surface using an open-ended coaxial sensor connected with a microwave network analyzer operating in the frequency range from 1.0 to 8.5 GHz. The dielectric properties (permittivity (dielectric constant, ε' and dielectric loss, ε")) were related to the physicochemical properties during the fruit maturity stage from week 6 to week 10. Width, length, mass, volume and SSC values increased, while moisture content (m.c.) and density values decreased with maturity stage (time). Permittivity values decreased with m.c. (and maturity stage), in agreement with theory in which permittivity of moist materials is a function of moisture content, density and frequency. Calibration equations were also established between the ε', ε" and m.c., and were found to be the most accurate at 1.0 GHz. The m.c. is used to assess watermelon quality since it produced high accuracy based on dielectric measurement. In conclusion, this technique showed potential to assess fruits' physicochemical and dielectric properties, then the maturity stage.

Keywords: open-ended coaxial sensor; microwave network analyzer; permittivity; moisture content; frequency; maturity stage

I. INTRODUCTION

Fruit internal quality indices are greatly dependent on internal disorder, sugar content, maturity/ripeness, firmness, freshness, density and so forth (Butz *et al.*, 2005; Sun *et al.*, 2010). However, fruit external characteristic may not directly proportional to their internal quality. In the last decades, the internal quality of fruit was typically assessed via human experience with issue on accuracy, slow process, high labor cost (Sun *et al.*, 2010) and destructive. Thus, an accurate, rapid, cost-effective and non-destructive method is vital.

To date, numerous literatures have reported on the different techniques of non-destructive analysis of food. Non-destructive techniques (NDT) for fruit internal quality assessment, in particular, include acoustic, spectroscopic (near infrared (NIR)), electrical, magnetic resonance, X-ray and computed tomography (Butz *et al.*, 2005; Ruiz-Altisent *et al.*, 2010; Sun *et al.*, 2010). These techniques do not require fruit cutting process nor pressing, hence will not destroy the fruit.

Dielectric characterization of agri-food produces is relatively a new method, and is finding increasing application (Jamaludin *et al.*, 2014b; Venkatesh & Raghavan, 2005). Fruit and vegetable, grain and seed,

*Corresponding author's e-mail: masniza@mardi.gov.my

beverage, baked food and flour, dairy product, fish and meat are important agri-food produces investigated. For any material, dielectric properties vary with moisture content, density, composition and structure, water activity, temperature, and frequency of the applied field (Ragni *et al.*, 2006). In dielectric measurement, the structure of biological tissue can be modeled as a simplified electrical circuit diagram consisting of parallel circuit of capacitor and resistor (Jamaludin *et al.*, 2014a; Kuson & Terdwongworakul, 2013). The most applied devices and instruments to measure dielectric properties of agri-food materials include the parallel plate capacitor, coaxial probe, waveguide, resonant structure, inductance capacitance-resistance (LCR) meter, impedance analyzer, and scalar and network analyzer (Ragni *et al.*, 2006; Soltani *et al.*, 2011). Permittivity (dielectric constant, *ε*' and dielectric loss, *ε*") and impedance are examples of dielectric parameters used in material characterization (Jamaludin *et al.*, 2014b; Khaled *et al.*, 2015). Variation in fruit shape and mass is reported as the difficulty associated in setting up methodology, instrument and statistical model based on the dielectric properties to predict agri-food produces quality (Ragni *et al.*, 2006).

Recent dielectric measurement based-research includes determination of fruit ripening/maturity stage (of durian (Kuson & Terdwongworakul, 2013), banana (Jamaludin *et al.*, 2014b)), moisture content (of Labisia pumila) (Jamaludin *et al.*, 2014a), sweetness/soluble solid content (of watermelon) (Kato, 1997; Nelson *et al.*, 2007), and so forth. Measurement of moisture content remains the prime interest in the application of dielectric properties to agri-food produces (Ragni *et al.*, 2006).

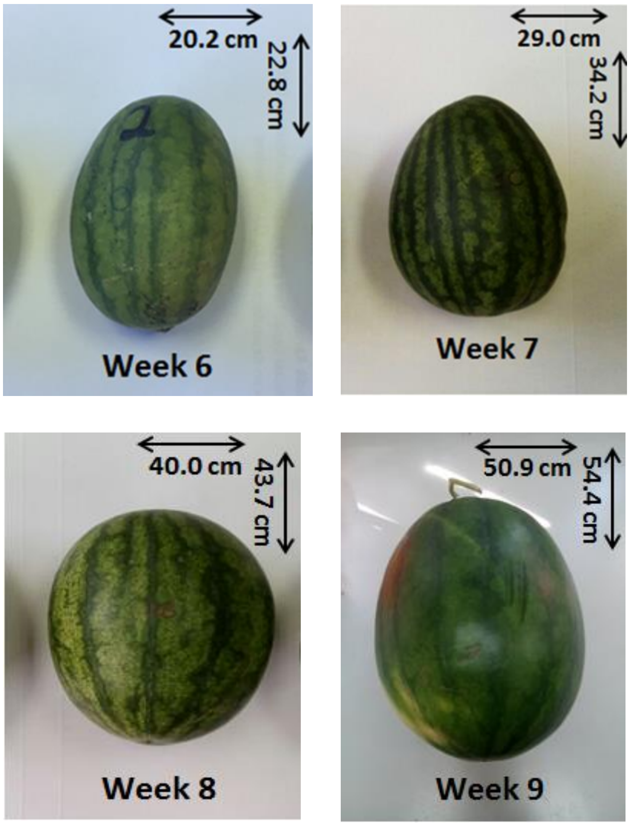
Watermelon is listed as 15 important commodities in National Agro-Food Policy (2011-2020) with the estimated production for 2017 of 208,343 MT (Jabatan Pertanian Malaysia, 2017). The major indices of watermelon internal qualities are soluble solid content (SSC), firmness, maturity and internal disorder (hollowness problem) (Kato, 1997).

In this study, the dielectric properties (*ε*' and *ε*") will be investigated and related to watermelon internal quality (maturity stage). The first part will cover the variation in watermelon physicochemical properties (width, length, mass, volume, density, moisture content (m.c.) and soluble solid content (SSC)) with time (week) after planting during fruit development. The second part will discuss the effects of moisture content and frequency on the *ε*' and *ε*", then establish the relationships between physicochemical and dielectric properties. These relationships can then be applied in the assessment of watermelon maturity stage.

II. MATERIALS AND METHODS

A. Sample Preparation

15 red watermelon samples (*Citrullus lanatus* cv. *Sugar Baby*) were freshly picked at 1-week interval starting week 6 to week 10 after planting (February to March 2017) from watermelon plot at Selangor Fruit Valley, Selangor (Figure 1). At every interval, three watermelon samples were randomly picked, each from different trees.



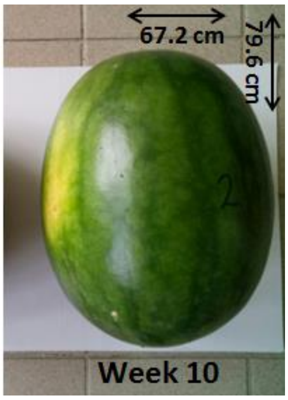


Figure 1. Watermelon development at weekly interval

B. Physicochemical Properties Measurement

The physicochemical properties of watermelon samples were measured at Engineering Research Centre, MARDI and Faculty of Science, UPM. The measurement of watermelon samples mass and size were performed using electronic weight balance and CD-6"PS digital caliper (Mitutoyo Corp., Japan), respectively. The size of each sample was evaluated by measuring the width and length as illustrated in Figure 1.

The microwave oven-drying method was used to determine the actual m.c. of watermelon using the official AOAC method (AOAC, 2000; Nielsen, 2010) with two minor modifications on time and power setting. The samples were sliced into the size of approximately 3 cm x 3 cm x 3 cm for m.c. analysis as shown in Figure 2. Before the drying process, each part of the samples was weighed separately using a Shimadzu Y220 electronic weight balance (Shimadzu Corp., Japan) with 0.1 mg precision. Each sample was then dried for 20 minutes with 550W microwave power. The dried samples were cooled at room temperature of 25 °C before being weighed again. The process was repeated until no significant change in m.c. was detected to ensure the determination of the actual m.c. was accurate. The wet basis m.c. of a material is defined as in Equation 1 (Bouraoui *et al.*, 1993):

$$Moisture\ content\ (\%) = \frac{m_{wet} - m_{dry}}{m_{wet}} 100\% \tag{1}$$

where m_{wet} and m_{dry} are the initial mass before drying and the final mass after drying, respectively.

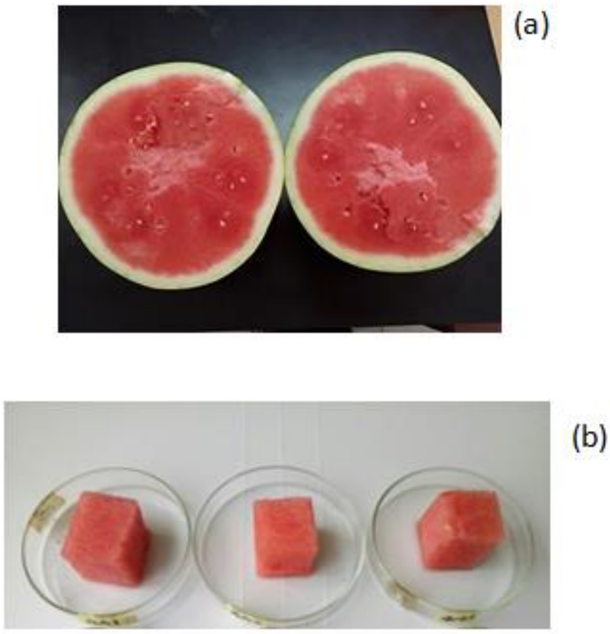


Figure 2. Sample preparation for moisture content analysis

Soluble solid content were measured in juice form of watermelon flesh with hand held AR 200 digital refractometer (Reichert Inc., New York, USA). SSC measurement was conducted to measure fruit sweetness level and represent by the degree of Brix (°Bx) (Guo *et al.*, 2011). Watermelon flesh samples were taken from the centre, avoiding the seed bearing region. SSC measurement was conducted by placing watermelon juice onto the refractometer prism surface. Every sample was measured in three duplicates then averaged.

Watermelon volume was determined using water displacement method. On the other hand, watermelon density was determined from calculation using standard equation.

C. Dielectric Properties Measurement

The measurement was performed at Engineering Research Centre, MARDI. The dielectric properties were measured using Agilent (now Keysight Technologies) 85070B open-ended coaxial (OEC) sensor (Keysight Technologies, Inc., California) along with a HP 8720B Vector Network Analyzer (VNA) (Keysight Technologies, Inc., California) ranging from 1.0 to 8.5 GHz. The calibration standards for the OEC sensor were air, a shorting block and deionized water. The surface and internal tissue of watermelon samples (thickness of 3 cm) were supported using a laboratory jack that was raised to bring the sample into firm and close contact with the sensor (Figure 3). The coaxial cable and sensor were fixed using a retort stand since any subtle movement could affect the measurement results. A computer was used to control the system and collect the data.

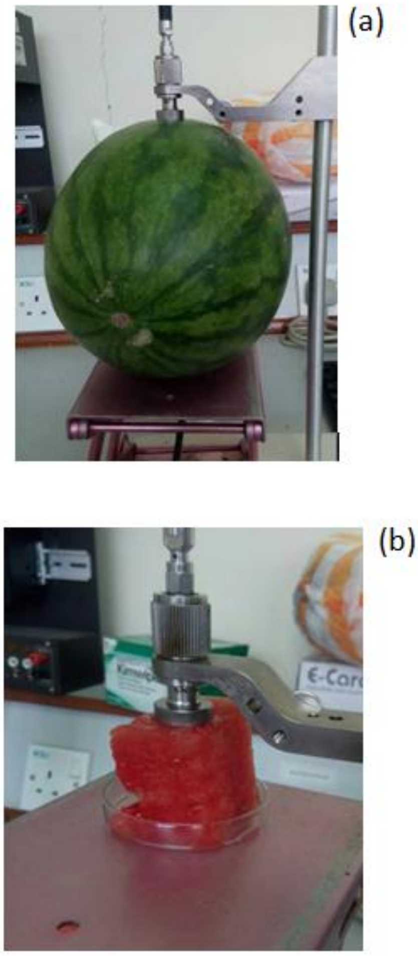


Figure 3. Dielectric properties measurement at the (a) surface, and (b) internal tissue of watermelon samples

III. RESULTS AND DISCUSSION

A. Physicochemical Properties of Watermelon

The physicochemical properties of watermelon samples measured from week 6 to week 10 were tabulated in Table 1. The samples could be categorized into unripe, half-ripe and ripe based on practice at watermelon farm.

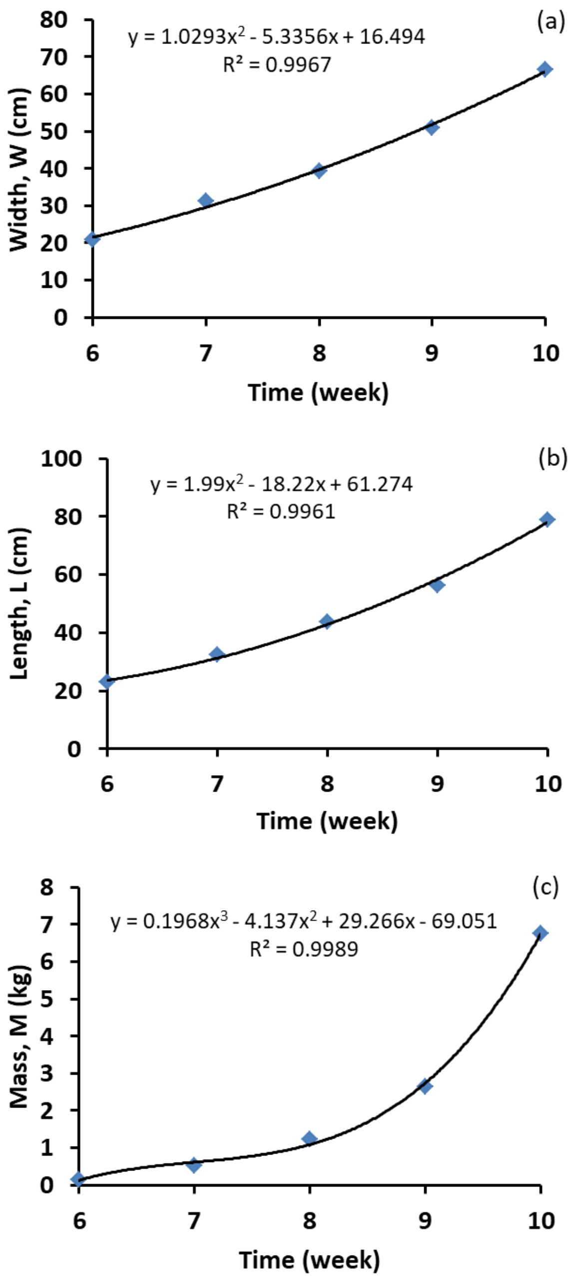
The width (W), length (L), mass (M) and volume (V) of watermelon increased over the 10 weeks of fruit development process due to accumulation of water, sugar and acid (Table 1) (Léchaudel & Joas, 2007). In addition, fruit can increase in mass or volume by 100-fold or more from fertilization to maturity due to the development of several organs and different tissue types (Seymour *et al.*, 2013). The variations of width, length, mass and volume with time (week) were best represented by polynomial equations (Figure 4 (a) – (d)). Generally, the earlier stage of fruit development showed rapid growth rate of the W, L, M and V, and slowly converged to constant value in the later stage.

On the other hand, the density and m.c. of unripe watermelon decreased with time then increased slightly as it ripens (Figure 4 (e) – (f)). According to the Federal Agricultural Marketing Authority (FAMA), Malaysia, the unripe watermelon has higher density, might be due to the higher moisture content (Sabeetha *et al.*, 2017). The density decreased during fruit development (week 6 to week 9) since the moisture content also decreased. Generally, water is often lost from the skin through transpiration however it also has the tendency to move from the skin to the pulp. The increase in osmotic transfer of moisture from skin to pulp might contribute to the increase in m.c. of fruit during ripening (Asiedu, 1987), in this case at week 10. The variation of density and m.c. were best represented by polynomial relationships.

SSC of watermelon also increased over the 10 weeks of fruit development process (Figure 4 (g)). This might be due to the metabolism of the fruits during development process (Jagtiani *et al.*, 1988). The increase in SSC could be attributed by the increase in sugar-to-acid ratio and soluble sugars (Lamsal & Jindal, 2014), and the breakdown of carbohydrate into simple sugar and glucose (Gill *et al.*, 2017; Kittur *et al.*, 2001) hence increases the sweetness level of watermelon during fruit development. The variation of SSC was best represented by polynomial relationship.

The W, L, M, m.c. and SSC of the ripe watermelon at week 10 was 66.6 cm, 79.0 cm, 6.765 kg, 92.19 % and 10.850 °Bx, respectively. These values are comparable to the published data for W 80.2 cm, L 80.5 cm, M 7.0 – 8.0 kg (Isa *et al.*, 2009), m.c. 91.0 % and SSC 11.4 °Bx (Nelson *et al.*, 2008).

Technically, fruit ripeness is usually represented by SSC value (Ibrahim *et al.*, 2017). However, SSC measurement is destructive technique. In contrast, m.c. in this study can be determined non-destructively using an open-ended coaxial sensor from calibration equations relating m.c. to the measured permittivity.



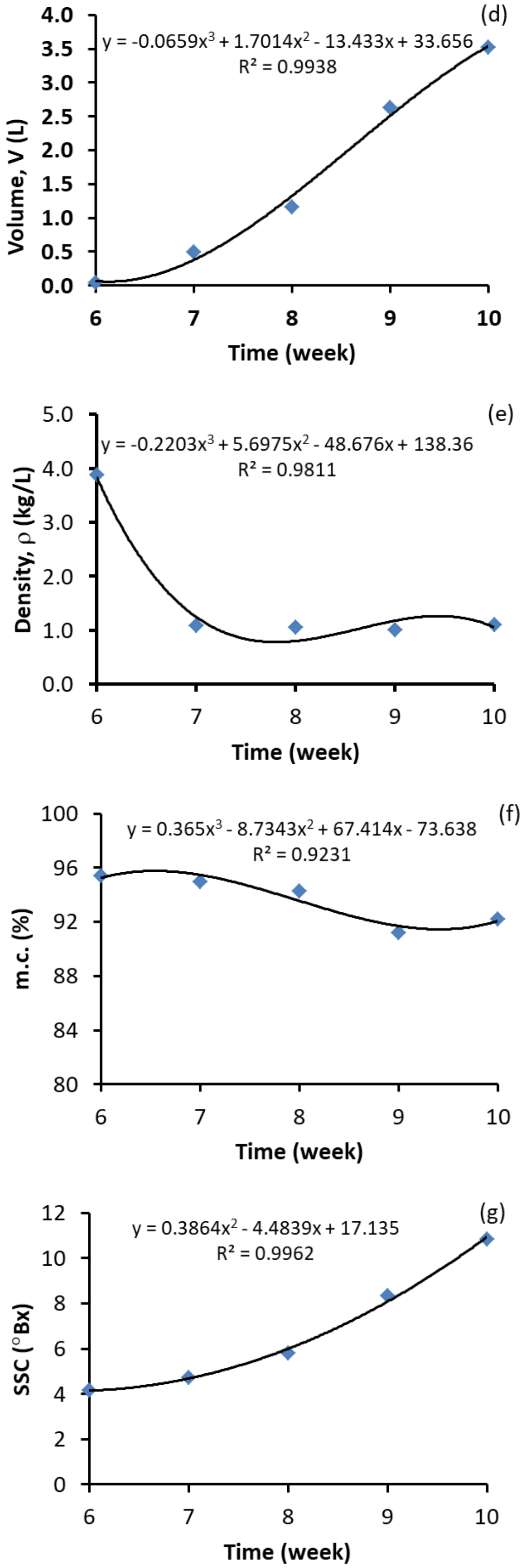


Figure 4. Relationship between (a) W, (b) L, (c) M, (d) V, (e) density (f) m.c., and (g) SSC with time (ripening weeks) of the watermelon samples

Table 1. Physicochemical properties of watermelon samples

Ripeness stage	Time (week)	Width (cm) (± std. dev.)	Length (cm) (± std. dev.)	Mass (kg) (± std. dev.)	Volume (L) (± std. dev.)	Density, ρ (± std. dev.)	m.c. (%) (± std. dev.)	SSC (°Bx) (± std. dev.)
Unripe	6	20.85± 0.919	22.90± 0.141	0.151± 0.015	0.039± 0.039	3.870 ± 0.038	95.37± 0.611	4.156± 0.574
	7	31.10± 3.112	32.40± 1.512	0.528 ± 0.043	0.490 ± 0.053	1.077 ± 0.043	94.99 ± 0.425	4.720 ± 0.245
Half-ripe	8	39.23± 0.759	43.57± 0.262	1.216 ± 0.056	1.161 ± 0.051	1.047 ± 0.005	94.28 ± 1.448	5.780 ± 0.887
	9	50.93± 0.368	56.40± 1.925	2.654 ± 0.194	2.623 ± 0.179	1.012 ± 0.009	91.21 ± 0.927	8.330 ± 0.532
Ripe	10	66.60± 0.600	79.00± 0.600	6.765 ± 0.020	3.514 ± 2.410	1.092 ± 0.005	92.19 ± 1.215	10.850 ± 0.050

B. Correlation between m.c. and SSC

Figure 5 shows the SSC and m.c. of watermelon was in good correlation. The m.c. decreased as the SSC increased. Similar trend was found in other fruits such as apple (Guo *et al.*, 2007) and honeydew melons (Nelson *et al.*, 2006). The R-value for the linear regression of the watermelon samples (five different stages of measurement) was 0.8418.

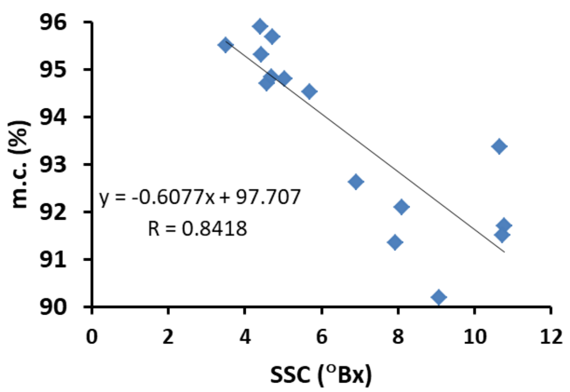


Figure 5. Correlation between m.c. and SSC

C. Dielectric Properties of Watermelon

The dielectric properties of watermelon measured on its external surface are illustrated in Figure 6(a) and (b). Figure 6(a) shows that the dielectric constant, ε' during fruit development (from week 6 to week 10) decreased with increasing frequency from 1.0 to 8.5 GHz. This suggested the ε' profile of the watermelon samples at all development time followed closely the ε' profile of water. The dielectric constant which is usually defined as the ability to store energy is lower at higher frequencies, in this case at 8.5 GHz for water and watermelon samples. This is due to the electric polarization of water in which it is highly influenced by the operating frequency (El Khaled *et al.*, 2016). Water molecules are able to follow the vibration of microwave at low frequency, thus increases the value of ε'. In contrast, the molecules are no longer able to follow the vibration of microwave at high frequency and energy is dissipated as heat and resulting in lower values of ε' (Kraszewski, 2005). The trend was similarly observed in other studies (Nelson *et al.*, 2008; Suhaime *et al.*, 2018).

The dielectric loss, ε'' influences both energy absorption and reflection, and describes the ability to dissipate energy in response to an applied electric field or various polarization mechanisms, which commonly results in heat generation (Ikediala *et al.*, 2000; Mudgett, 1986). In this study, the ε'' generally decreased with frequency, then increased slightly as frequency approached 8.5 GHz (Figure 6(b)). The turning known as the critical frequency, f_c (can be determined using linear projection method), separates the bound and free water molecules. This is due to the relaxation effect which usually related to the orientation of polarization. Previous study has reported similar permittivity trend with frequency on watermelon surface and internal tissue (Nelson *et al.*, 2008).

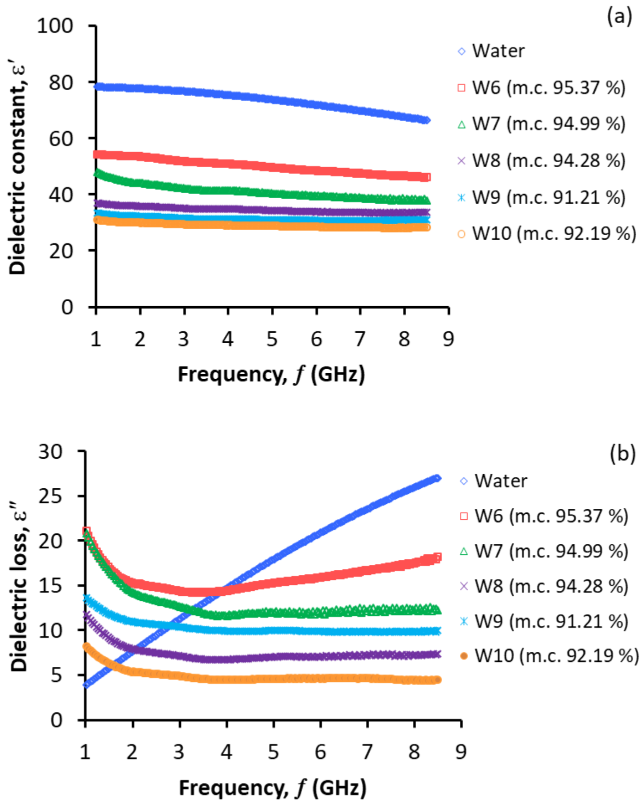
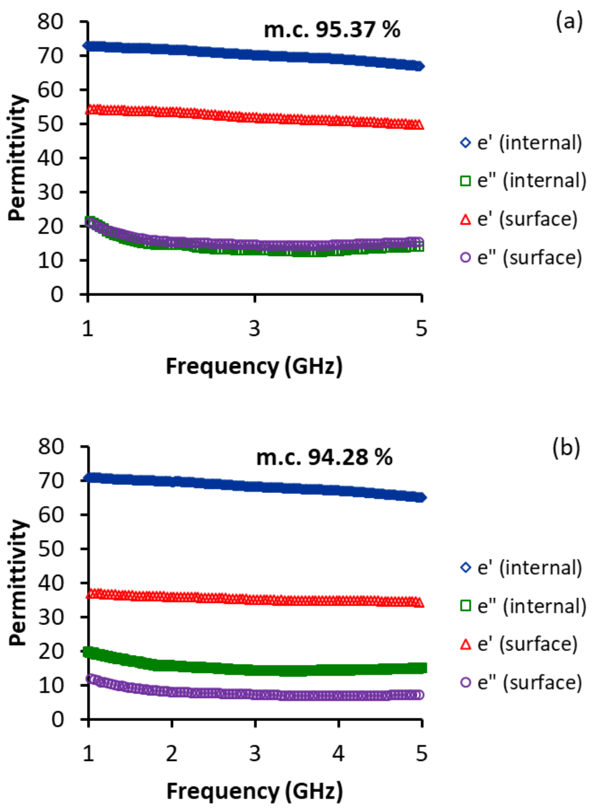


Figure 6. Variations in (a) ε', and (b) ε" with frequency at five values of m.c. during watermelon development process. W represents week

The *ε*' and *ε*" values decreased with maturity stage/time (as watermelon ripens) since the moisture content decreased (from week 6 to week 10). This is in agreement with theory in which permittivity of moist materials is a function of moisture content, density and frequency (Mohan *et al.*, 2015). In general, the dielectric properties of food decreased rapidly with decreasing moisture content (Nelson, 2015; Tang, 2005). The permittivity was reported to depend mainly on moisture content as influenced by frequency, temperature, density and sample size (Venkatesh & Raghavan, 2005).

D. Comparison of Dielectric Properties Measured at Surface and Internal Tissue

Figure 7 presents the variances of the permittivity values between measurement at watermelon's surface and internal tissue at three ripening stages i.e. unripe, half-ripe and ripe. It showed the highest differences of dielectric constant and dielectric loss values for measurement at watermelon's surface and internal tissue towards the ripe stage (towards low m.c.). Dielectric properties from surface measurement had lower values than those for the internal tissues as similarly observed by (Nelson *et al.*, 2008). Both surface and internal measurements exhibit similar trends with frequency. The watermelon internal tissue has higher moisture content as compared to the surface, hence producing higher *ε*' and *ε*" values. However, in this study, measurement from watermelon surface is preferable to produce non-destructive approach.



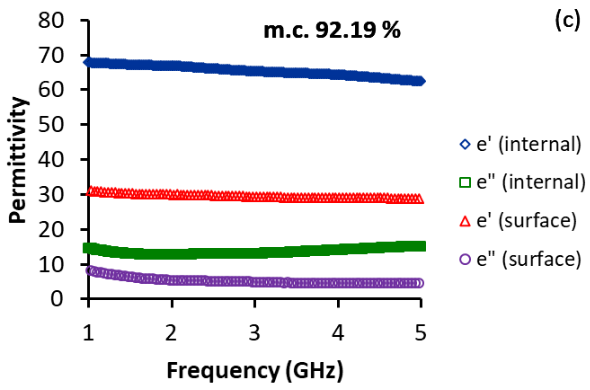


Figure 7. Measured permittivity at the surface and internal tissue of (a) unripe, (b) half-ripe and (c) ripe watermelon samples

The dielectric properties of the surface and internal measurements at 1.0 GHz are comparable with published data as listed in Table 2. Lack of information on dielectric properties during watermelon development stage, thus the obtained data only compares the ripe watermelon stage.

Table 2. Comparison of the ε' and ε" values measured experimentally and published data

	Surface		Internal tissue	
	ε'	ε"	ε'	ε"
Experimental	31	8	67	14
Published data (Nelson *et al.*, 2008)	38	10	70	13

E. Performance Analysis

Calibration equations were established to predict m.c. from the dielectric properties measurement at watermelon's surface at three selected frequencies (1.0, 3.0 and 5.0 GHz). The calibration equations are listed in Table 3 (a) ε', and (b) ε". The regression coefficients, R^2 of the calibration equations for ε' was the biggest at the highest operating frequency, i.e. at 5.0 GHz and contrarily for ε". This might be due to the effect of bound water at low frequency especially below 2.0 GHz (Cheng *et al.*, 2018; Hassan *et al.*, 1997). High R^2 value indicates high correlation between dielectric properties of watermelon's surface with m.c. of internal tissue. However, it should be noted that high correlation does not guarantee high accuracy. The accuracy of the calibration model in predicting the m.c. was calculated by comparing the predicted m.c. obtained from dielectric properties measurement with the actual m.c. using microwave oven drying method. The accuracy is frequently represented by relative error. The relative error can be calculated as follows (Ansarudin *et al.*, 2012):

$$\text{Relative error} = \frac{\text{m.c.}_{actual} - \text{m.c.}_{predicted}}{\text{m.c.}_{actual}} \quad (2)$$

where m.c. *predicted* and m.c. *actual* are the predicted and actual m.c. obtained using calibration equation model and microwave oven drying method, respectively.

The calibration equations based on both ε' and ε" were found to be the most accurate at 1.0 GHz with mean relative error of 2.7 % and 2.1 %, respectively. Thus, it can be concluded that the most accurate equation to predict m.c. in the watermelon samples is based on the measurement of the ε" at 1.0 GHz.

Table 3. Calibration equations relating m.c. to (a) ε' (b) ε"

(a)

Frequency (GHz)	ε'	R^2	Mean relative error (%)
1	m.c. = $0.0001\,\varepsilon'^3 - 0.0190\,\varepsilon'^2 + 1.3215\,\varepsilon' + 66.4977$	0.8072	2.7
3	m.c. = $-0.0004\,\varepsilon'^3 + 0.0340\,\varepsilon'^2 - 0.7149\,\varepsilon' + 92.8025$	0.8232	6.0
5	m.c. = $-0.0009\,\varepsilon'^3 + 0.0892\,\varepsilon'^2 - 2.7042\,\varepsilon' + 116.4762$	0.8241	8.0

(b)

Frequency (GHz)	ε"	R^2	Mean relative error (%)
1	m.c. = $0.0236\,\varepsilon''^2 - 0.5120\,\varepsilon'' + 95.2378$	0.5828	2.1
3	m.c. = $0.0615\,\varepsilon''^2 - 0.9164\,\varepsilon'' + 95.9222$	0.4213	2.2
5	m.c. = $0.0293\,\varepsilon''^2 - 0.324\,\varepsilon'' + 93.5811$	0.3908	3.0

IV. CONCLUSION

The application of an open-ended coaxial sensor for the assessment of physicochemical and dielectric properties of watermelon has been studied. The dielectric constant and dielectric loss were related to the m.c. from week 6 to week 10 during watermelon development. Permittivity values at frequencies from 1.0 to 8.5 GHz showed that the dielectric constant and dielectric loss decreased with increasing frequency and decreasing m.c. The relationships between permittivity, frequency and m.c. have been established. The technique showed potential for the development of non-destructive and speedy initial quality check of fruit maturity stage based on moisture content. A portable microwave measurement system shall be constructed soon to replace the VNA for *in situ* measurements.

V. ACKNOWLEDGEMENT

This research was supported by Ministry of Higher Education of Malaysia (MOHE) (FRGS/1/2015/TK02/MOA/02/1). The authors would like express utmost gratitude to MARDI and UPM for the use of facilities for the research. The gratitude is also extended to Selangor Fruit Valley for the watermelon samples and for the staff assistance during the sampling process.

VI. REFERENCES

Ansarudin, F, Abbas, Z, Hassan, J, Yahaya, N & Ismail, M 2012, 'A simple insulated monopole sensor technique for determination of moisture content in hevea rubber latex', *Measurement Science Review*, vol. 12, no. 6, pp. 249-254.

AOAC 2000, *Official methods of analysis of the Association of Official Analytical Chemists*, 17th edition. AOAC International, Arlington VA.

Asiedu, J 1987, 'Physicochemical changes in plantain (*musa paradisiaca*) during ripening and the effect of degree of ripeness on drying', *Tropical Science*. vol. 27, pp. 249–260.

Bouraoui, M, Richard, P & Fichtali, J 1993, 'A review of moisture content determination in foods using microwave oven drying', *Food Research International*, vol. 26, no. 1, pp. 49-57.

Butz, P, Hofmann, C & Tauscher, B 2005, 'Recent developments in noninvasive techniques for fresh fruit and vegetable internal quality analysis', *Journal of Food Science-Chicago*, vol. 70, no. 9, p. R131.

Cheng, EM, Shahriman, AB, Rahim, HA, Abdul Malek, MF, Mohd Nasir, NF, Abdulaziz, N, Abdul Majid, MS & Basaruddin, KS 2018, 'Microwave reflection based dielectric spectroscopy for moisture content in melele mango fruit (*mangifera indica l.*)', *Journal of Telecommunication, Electronic and Computer Engineering*, vol. 10, no. 1-14, pp. 1-6.

El Khaled, D, Castellano, N, Gázquez, J, Perea-Moreno, A-J & Manzano-Agugliaro, F 2016, 'Dielectric spectroscopy in biomaterials: Agrophysics', *Materials*, vol. 9, no. 5, p. 310.

Gill, P, Jawandha, S, Kaur, N & Singh, N 2017, 'Physico-chemical changes during progressive ripening of mango (*mangifera indica l.*) cv. Dashehari under different temperature regimes', *Journal of Food Science and Technology*, vol. 54, no. 7, pp. 1964-1970.

Guo, W-c, Nelson, SO, Trabelsi, S & Kays, SJ 2007, '10–1800-MHz dielectric properties of fresh apples during storage', *Journal of Food Engineering*, vol. 83, no. 4, pp. 562-569.

Guo, W, Zhu, X, Nelson, SO, Yue, R, Liu, H & Liu, Y 2011, 'Maturity effects on dielectric properties of apples from 10 to 4500 MHz', *LWT-Food Science and Technology*, vol. 44, no. 1, pp. 224-230.

Hassan, J, Khalid, K & Yusoff, WMDW 1997, 'Microwave dielectric properties of hevea rubber latex in the temperature range of-30 C to 50 C', *Pertanika Journal of Science & Technology*, vol. 5, no. 2, pp. 179-190.

Ibrahim, N, Abd Aziz, S & Nawi, N 2017, 'Novel impedance measurement technique for soluble solid content determination of banana', *Pertanika Journal of Science and Technology*, vol. 25, no. 2, pp. 519-526.

Ikediala, J, Tang, J, Drake, S & Neven, L 2000, 'Dielectric properties of apple cultivars and codling moth larvae', *Transactions of the ASAE*, vol. 43, no. 5, p. 1175.

Mohd Isa, M, Ibrahim, N, Shamsudin, R & Marhaban, MH 2009, 'Sugar content in watermelon juice based on dielectric properties at 10.45 GHz': *2009 IEEE Student Conference on Research and Development (SCOReD 2009),* UPM, Serdang, Selangor, pp. 529-532.

Jabatan Pertanian Malaysia 2017, *Statistik tanaman (sub-sektor tanaman makanan) 2017*. Jabatan Pertanian Malaysia, Putrajaya, Malaysia.

Jagtiani, J, Chan, H & Sakai, W 1988, 'Mango in tropical fruit processing'. Academic Press Inc., San Diego, California, USA.

Jamaludin, D, Abd Aziz, S, Ahmad, D & Jaafar, H 2014a, 'Impedance characteristics of labisia pumila plant water stress': *National Conference on Agricultural and Food Mechanization 2014 (NCAFM 2014)*, Kota Kinabalu, Sabah, pp. 319-325.

Jamaludin, D, Abd Aziz, S & Ibrahim, NUA 2014b, 'Dielectric based sensing system for banana ripeness assessment', *International Journal of Environmental Science and Development*, vol. 5, no. 3, pp. 286-289.

Kato, K 1997, 'Electrical density sorting and estimation of soluble solids content of watermelon', *Journal of Agricultural Engineering Research*, vol. 67, no. 2, pp. 161-170.

Khaled, D, Novas, N, Gazquez, J, Garcia, R & Manzano-Agugliaro, F 2015, 'Fruit and vegetable quality assessment via dielectric sensing', *Sensors*, vol. 15, no. 7, pp. 15363-15397.

Kittur, F, Saroja, N & Tharanathan, R 2001, 'Polysaccharide-based composite coating formulations for shelf-life extension of fresh banana and mango', *European Food Research and Technology*, vol. 213, no. 4, pp. 306-311.

Kraszewski, AW 2005, 'Recent developments in electromagnetic aquametry', in Kupfer, K (ed), *Electromagnetic aquametry. Electromagnetic wave interaction with water and moist substances*. Germany: Springer, 1-12.

Kuson, P & Terdwongworakul, A 2013, 'Minimally-destructive evaluation of durian maturity based on electrical impedance measurement', *Journal of Food Engineering*, vol. 116, no. 1, pp. 50-56.

Lamsal, BP & Jindal, VK 2014, 'Variation in electrical conductivity of selected fruit juices during continuous ohmic heating', *KMUTNB International Journal of Applied Science and Technology*, vol. 7, no. 1, p. 47.

Léchaudel, M & Joas, J 2007, 'An overview of preharvest factors influencing mango fruit growth, quality and postharvest behaviour', *Brazilian Journal of Plant Physiology*, vol. 19, no. 4, pp. 287-298.

Mohan, RR, Paul, B, Mridula, S & Mohanan, P 2015, 'Measurement of soil moisture content at microwave frequencies', *Procedia Computer Science*, vol. 46, no., pp. 1238-1245.

Mudgett, RE 1986, 'Electrical properties of foods', *Engineering Properties of Foods*, vol. 2, no., pp. 389-455.

Nelson, S 2015, *Dielectric properties of agricultural materials and their applications*. Academic Press, USA.

Nelson, S, Trabelsi, S & Kays, S 2008, 'Dielectric spectroscopy of melons for potential quality sensing', *Transactions of the ASABE*, vol. 51, no. 6, pp. 2209-2214.

Nelson, SO, Guo, W-c, Trabelsi, S & Kays, SJ 2007, 'Dielectric spectroscopy of watermelons for quality sensing', *Measurement Science and Technology*, vol. 18, no. 7, p. 1887.

Nelson, SO, Trabelsi, S & Kays, SJ 2006, 'Dielectric spectroscopy of honeydew melons from 10 MHz to 1.8 GHz for quality sensing', *Transactions of the ASABE*, vol. 49, no. 6, pp. 1977-1981.

Nielsen, SS 2010, 'Determination of moisture content', *Food analysis laboratory manual* Springer, 17-27.

Ragni, L, Gradari, P, Berardinelli, A, Giunchi, A & Guarnieri, A 2006, 'Predicting quality parameters of shell eggs using a simple technique based on the dielectric properties', *Biosystems Engineering*, vol. 94, no. 2, pp. 255-262.

Ruiz-Altisent, M, Ruiz-Garcia, L, Moreda, GP, Lu, R, Hernandez-Sanchez, N, Correa, EC, Diezma, B, Nicolaï, B & García-Ramos, J 2010, 'Sensors for product characterization and quality of specialty crops - a review', *Computers and Electronics in Agriculture*, vol. 74, no. 2, pp. 176-194.

Sabeetha, S, Amin, I & Nisak, MB 2017, 'Physico-chemical characteristics of watermelon in malaysia', *Journal of Tropical Agriculture and Food Science*, vol. 45, no. 2, pp. 209-223.

Seymour, GB, Østergaard, L, Chapman, NH, Knapp, S & Martin, C 2013, 'Fruit development and ripening', *Annual Review of Plant Biology*, vol. 64, pp. 219-241.

Soltani, M, Alimardani, R & Omid, M 2011, 'Use of dielectric properties in quality measurement of agricultural products', *Nature and Science*, vol. 9, no. 4, pp. 57-61.

Suhaime, N, Sairi, M, Abbas, Z, Nafis, NBM, Othman, Z, Adnan, ASM, Shamsulkamal, AR, Paiman, S & Mohamed, TN 2018, 'Microwave technique for moisture content and pH determination during pre-harvest of mango cv. Chok anan', *Sains Malaysiana* vol. 47, no. 7, pp. 1571-1578.

Sun, T, Huang, K, Xu, H & Ying, Y 2010, 'Research advances in nondestructive determination of internal quality in watermelon/melon: A review', *Journal of Food Engineering*, vol. 100, no. 4, pp. 569-577.

Tang, J 2005, 'The microwave processing of foods; Schubert, H, and Regier, M Eds'. Woodhead Publishing Limited: Cambridge, UK.

Venkatesh, M & Raghavan, G 2005, 'An overview of dielectric properties measuring techniques', *Canadian Biosystems Engineering*, vol. 47, no. 7, pp. 15-30.