UNIVERSITI PUTRA MALAYSIA

OPEN-ENDED COAXIAL SENSOR FOR DETERMINATION OF MOISTURE CONTENT, SOLUBLE SOLID CONTENT, pH AND DIELECTRIC PROPERTIES OF Chok Anan MANGO

NORADIRA BINTI SUHAIME

FS 2018 58

OPEN-ENDED COAXIAL SENSOR FOR DETERMINATION OF MOISTURE CONTENT, SOLUBLE SOLID CONTENT, pH AND DIELECTRIC PROPERTIES OF *Chok Anan* MANGO

By

NORADIRA BINTI SUHAIME

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

May 2018

DEDICATION

This thesis is dedicated to my beloved husband (Abdul Rahman Che Nordin), my little daughter (Nur Haura Saffiya)

My dear parents (Suhaime Musa & Salma Mat Salleh) and Brothers....

Thanks for the supporting and your encouragements..

Adira Suhaime

2018

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

OPEN-ENDED COAXIAL SENSOR FOR DETERMINATION OF MOISTURE CONTENT, SOLUBLE SOLID CONTENT, pH AND DIELECTRIC PROPERTIES OF *Chok Anan* MANGO

By

NORADIRA BINTI SUHAIME

May 2018

Chairman: Associate Professor Zulkifly Abbas, PhD

Faculty: Science

The thesis presents the application of open-ended sub-miniature panel (SMA-P) coaxial sensor to determine moisture content, soluble solid content, pH and dielectric properties of *Chok Anan* mango during ripening from week 5 to week 17 based on reflection coefficient ($|S_{11}|$) measurement in the frequency range between 1.0 GHz to 4.0 GHz. Measurements were conducted using Keysight FieldFox N9912A Network Analyzer. The mass (*M*), width (*W*), length (*L*), moisture content (m.c.), soluble solid content (SSC) and pH of *Chok Anan* mango were also measured. All the measured parameters were found to increase non-linearly from week 5 to week 17. This work focus on the internal properties of mango (m.c., pH and SSC) since the external properties (*M*, *W*, and *L*) may not truly represent its internal quality. The SSC and pH methods are only suitable for measurement at later stage of fruit ripeness, i.e. after week 16, which is too late to determine the ripening stage of mango fruits. In contrast, m.c. profiles was distinctively clear to distinguish all the stages of fruit ripeness for the whole 17 weeks of fruit development. Besides that, SSC and pH methods are laborious, difficult, time consuming and destructive whilst the m.c. can be determine fast, accurate and non-destructive using SMA-P coaxial sensor from calibration equations relating to the m.c. to the measured $|S_{11}|$. The permittivity measurement for the different percentage of m.c. in mango is carried out using the Keysight 85070E dielectric probe kit, later the permittivity values obtained used as an input to calculate the $|S_{11}|$ using Finite Element Method (FEM). FEM was used to determine the accuracy of permittivity measurement by comparing the calculated values of $|S_{11}|$ using FEM with measurement results. Very closed agreements were obtained between measured and calculated $|S_{11}|$ where the mean errors were within 1.5% for all percentage of m.c.. Calibration equations were established to predict the m.c., dielectric constant (ε') and loss factor (ε'') from the measured $|S_{11}|$, where the accuracies for the m.c. and ε' were highest at 1.0 GHz within 1.5% and 1.6%, respectively, whilst ε'' was 3.4% at 4.0 GHz. Also, calibration equation has been established to predict pH and SSC values

from m.c. obtained from $|S_{11}|$ measurements. The accuracy of pH and SSC were within 3.0% and 5.2%, respectively when compared to standard techniques. The m.c. is the best parameter used to identify the quality of mango since it produced high accuracy based on $|S_{11}|$ measurements using SMA-P coaxial sensor. In conclusion, SMA-P coaxial sensor provides a simple, speedy, non-destructive, flexible and inexpensive approach for the determination of m.c., SSC, pH and permittivity in mango.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGESAN SEPAKSI HUJUNG TERBUKA UNTUK MENENTUKAN KANDUNGAN LEMBAPAN, KANDUNGAN PEPEJAL LARUT, pH DAN CIRI-CIRI DIELEKTRIK MANGGA Chok Anan

Oleh

NORADIRA BINTI SUHAIME

Mei 2018

Pengerusi: Professor Madya Zulkifly Abbas, PhD

Fakulti: Sains

Tesis ini membentangkan penggunaan pengesan sepaksi hujung terbuka *sub-mini panel* (SMA-P) untuk menentukan kandungan kelembapan, kandungan pepejal larut, pH dan ciri-ciri dielektrik mangga Chok Anan sepanjang kematangan dari minggu 5 hingga minggu 17 berdasarkan pengukuran pekali pantulan ($|S_{11}|$) dalam julat frekuensi antara 1.0 GHz hingga 4.0 GHz. Pengukuran telah dijalankan menggunakan Rangkaian Penganalisis Keysight FieldFox N9912A. Jisim (*M*), lebar (*W*), panjang (*L*), kandungan lembapan (m.c.), kandungan pepejal larut (SSC) dan pH mangga Chok Anan juga diukur. Semua parameter yang diukur didapati meningkat secara tidak linear dari minggu 5 ke minggu ke-17. Kajian ini memberi tumpuan kepada sifat dalaman mangga (m.c., pH dan SSC) kerana sifat luaran (*M*, *W*, dan *L*) mungkin tidak benar-benar mewakili kualiti dalamannya. Kaedah SSC dan pH hanya sesuai untuk pengukuran pada peringkat akhir kematangan buah iaitu selepas minggu ke-16 yang sudah terlambat untuk menentukan tahap masak buah mangga. Sebaliknya, m.c. profilnya adalah jelas untuk membezakan semua peringkat kematangan buah untuk keseluruhan 17 minggu perkembangan buah. Selain itu, kaedah SSC dan pH adalah sukar, memakan masa dan merosakkan sementara m.c. boleh menentukan cepat, tepat dan tidak merosakkan menggunakan sensor sepaksi SMA-P dari persamaan kalibrasi yang berkaitan m.c. dengan pengukuran $| S_{11} |$. Pengukuran ketelusan peratusan m.c. mangga yang berlainan dilakukan dengan menggunakan kit pengesan dielektrik Keysight 85070E, kemudian nilai pengukuran ketelusan yang diperolehi digunakan untuk pengiraan $|S_{11}|$ menggunakan Finite Element Method (FEM) atau Kaedah Unsur Terhingga. FEM digunakan untuk menentukan ketepatan pengukuran ketelusan dengan membandingkan nilai pekali pantulan yang dikira menggunakan FEM dengan hasil pengukuran. Hubungan yang sangat baik diperoleh di antara pekali pantulan yang diukur dan yang dikira dengan ralat relatif min adalah 1.5% untuk semua peratusan m.c. mangga. Persamaan penentukuran diwujudkan untuk meramalkan m.c., pemalar dielektrik (ε') dan faktor kerugian (ε'') daripada $| S_{11} |$ yang diukur, di mana ketepatan untuk m.c. dan

ε’ adalah tertinggi pada 1.0 GHz pada 1.5% dan 1.6%, manakala ε’’ ialah 3.4% pada 4.0 GHz. Selain itu, persamaan penentukuran telah diwujudkan untuk meramalkan nilai pH dan SSC dari nilai m.c. yang diperolehi dari pengukuran $|S_{11}|$. Ketepatan nilai pH dan SSC masing-masing adalah 3.0% dan 5.2%, berbanding dengan teknik standard. M.c. adalah parameter terbaik yang digunakan untuk mengenal pasti kualiti mangga kerana ia memberikan ketepatan yang tinggi berdasarkan pengukuran $|S_{11}|$ menggunakan pengesan sepaksi hujung terbuka SMA-P. Kesimpulannya, pengesan sepaksi hujung terbuka SMA-P adalah suatu pendekatan yang mudah, cepat, tidak merosakkan, fleksibel dan murah untuk menentukan m.c., SSC, pH dan ketelusan dalam mangga.

ACKNOWLEDGEMENTS

First of all, infinite gratitude I praise to Allah for giving me the strength and health to finish this thesis. I would like to express my greatest appreciation to my supervisor, Prof Madya Dr. Zulkifly Abbas have been most encouraging and accommodating with continual guidance's and support throughout this project. My special thanks to Dr. Masniza Sairi as my external co-supervisor which always contribute many ideas, time, and energy to make sure my master research going smoothly and perfectly even though busy with her routine schedule as a research officer at MARDI. Thanks to Dr. Suriati Paiman for her willingness to serve as my internal co-supervisor. Never to forget, my special thanks to the MARDI officer, Dr, Zaulia Othman, Mr. Amir Syariffuddeen Mhd Adnan and Mr. Amir Redzuan Shamsulkamal for their kind cooperation. I have learned a lot of experience from them during my research.

This research was supported by Ministry of Higher Education of Malaysia (MOHE) (FRGS/1/2015/TK02/MOA/02/1). I would like express utmost gratitude to the 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 mango samples and staff assistance during sampling process. Finally, thanks to Mr. Fadhilnor Abdullah (MARDI Perlis) for his assistance with data interpretation.

I would like to give my special thanks to my beloved husband (Abdul Rahman bin Che Nordin), my dear parents (Suhaime bin Musa and Salma binti Mat Salleh) and my siblings for their support and encouragements to carry out my education. To my special little daughter, Nur Haura Saffiya, thank you for indirectly teach me how to be a mom and student at the same time. I would like to express my deepest thanks to my best friend, Nur Biha who always keep supporting me, sharing problems together. Also to my lab mates, Tity Nazleen, Radzi, Sunday, Mehsen, Daw, Ahmad Khamis for their continuous support.

I certify that a Thesis Examination Committee has met on 28 May 2018 to conduct the final examination of Noradira binti Suhaime on her thesis entitled "Open-Ended Coaxial Sensor for Determination of Moisture Content, Soluble Solid Content, pH and Dielectric Properties of *Chok Anan* Mango" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Lim Kean Pah, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Rabaah Syahidah binti Azis, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Internal Examiner)

Huda Abdullah, PhD
Associate Professor
Universiti Kebangsaan Malaysia
Malaysia
(External Examiner)

RUSLI HAJI ABDULLAH, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 30 July 2018

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Zulkifly Abbas, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Suriati Paiman, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

Masniza Sairi, PhD
Associate Professor
Engineering Research Centre
Malaysian Agricultural Research and Development Institute (MARDI)
(Member)

____
ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: __________________

Name and Matric No.: ____

Declaration by Members of Supervisory Committee

This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
- Supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________
Name of Chairman of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

GDP	Gross Domestic Product
DOA	Department of Agriculture
FAMA	Federal Agricultural Marketing Authority
NAP3	Third National Agricultural Policy
MARDI	Malaysian Agricultural Research and Development Institute
IANS	Indo-Asian News Service
FAO	Food and Agricultural Organization of the United Nations
m.c.	Moisture content
NDE	Non-destructive evaluation
SSC	Soluble solid content
NIR	Near infrared
KOEC	Keysight open ended coaxial probe
SMA-P	Sub-miniature panel
FEM	Finite Element Method
$\|S_{11}\|$	Magnitude of reflection coefficient
Vis/NIR	Visible/Near Infrared
MoM	Method of Element
FDTD	Finite Difference Time Domain
$\vec{E}$	Electric field intensity
$\vec{H}$	Magnetic field intensity
$\vec{J}$	Electric current density
$\vec{D}$	Electric displacement
$\vec{B}$	The magnetic flux density
ρ_q	Charge density
ω	Angular frequency
Z	Impedance
$\tilde{Y}$	Admittance
S_{11}	Reflection coefficient
ε_c	Dielectric constant of the material filled in coaxial line
ε	Dielectric constant in external medium
a	Inner radius
b	Outer radius
k_o	Free space propagation constant
J_o	Bessel function of zeroth order
Si	Sine integral
N	Number of elements (NOEs)
V_e	Element potential typically approximated with polynomial equation
N	The number of nodes
α_i	The element shape function
V_{ei}	Potential at node *i*
RF	Radio Frequency
m_{wet}	Initial mass before drying
m_{dry}	Final mass before drying
M	Mass
L	Length

W	Width
°Bx	Brix
T	Time (ripening weeks)
ε'	Dielectric constant
ε''	Loss factor
f_c	Critical frequency
σ	Conductivity
ε_o	Permittivity in free space
F	Frequency
R^2	Regression coefficient
[K]	Sparse matrix
[b]	Excitation matrix

CHAPTER 1

INTRODUCTION

Agriculture remains as an important contributing sector to the Malaysian economy. In 2011, it provided employment opportunity for 13% of the population and contributed 10.5% to the national Gross Domestic Product (GDP). Within the agricultural sector, fruit industry has been identified as one of the rising stars with low commodity price and never-ending enthusiasm to broaden the agricultural base. The importance of the fruit industry to the national economy can be seen from its estimated high exportation value of nearly RM 4255.952 Mil in 2017 (DOA, 2017).

Malaysia is a tropical land that is blessed with abundant supply of various kind of tropical fruits such as pineapples, durians, watermelons, starfruits, bananas, papayas and mangoes. Its' tropical climate is perfect for the cultivation of various exotic fruits, especially in the Peninsular Malaysia since it rarely experiences hurricanes or droughts, thus increase the capability to boost tropical fruit exports. However, this depends on the fruits quality as well. Fruits quality is becoming increasingly important in the agriculture industry due to the competition among manufacturers and the growing expectation from the consumers.

Ever since fruits quality proves to be a real challenge in the expansion of the tropical fruits products, countless serious efforts have been taken to ensure the tropical fruits industry remains competitive. The quality of fruits varies depending on two factors which are environmental and humans, which play significant role mainly during the ripening, harvesting, storage, processing, packaging and transportation process. National Agro-Food Policy (2011-2020) and Third National Agricultural Policy (NAP3) (1998-2010) have listed 15 fruits that are considered as important commodities. One of them is mango, a local fruit that is to be cultivated by growers based on the demand and the requirements of marketing potential (Azlina et al., 2014).

Recently, there is a high demand for a specialized sensor to be developed for speedy and accurate assessment of fruit quality. Thus, the information regarding the relationship between fruits properties and its physical parameters that can be measured by a specialized sensor is deemed essential (Jha et al., 2011). In relation to that, the agricultural sector is highly interested in the application of microwave instrument. The application of the instrument is important since it can determine the ideal time for harvesting, perform rapid measurement of quality of certain products, and determine the condition of various points in processing and storage operations.

1.1 Mango, An Overview

Mango (*Mangiferaindica L.)* is one of the most popular tropical fruits and it belongs to the Anacardiaceae family with 60 genera (Abidin, 1991). Originally hailed from India, it widely spread to Malaya, eastern Africa and eastern Asia. Mango ranks second after banana in the tropical fruit production and land area usage (FAO, 2008)

Globally, over one hundred varieties are planted (Bally et al., 2009). In Malaysia, the most popular mango varieties planted are '*Harumanis*', '*Chok Anan*', '*Masmuda'* and 'MAHA'. Generally, the composition of mango consists of approximately 81% moisture, 0.4% fat, 0.6% proteins, 0.8% fibre and 17% carbohydrate. However, this composition pattern can be divided into three stages, which vary between cultivators, climatic and cultural factors (Quintana et al., 1984). Among the tropical fruits in Malaysia, mango is one of the most popular fruits. Besides its pungent and flavourful good taste, it also contains a lot of important minerals, highly nutritious and offers plenty of variety. Depending on the purpose, mango can be used either in its raw or ripe form. Generally, various traditional products can be prepared from raw mango such as raw mango slices soaked in brine, *amchur* (Indian spice powder), pickles and many more. As for ripe mango, besides the regular consumption, it is also used in the medical industry as digestive agent as it contains fattening, diuretic and laxative properties. Apart from the fruit itself, mango tree proves to be quite useful as well; the tree trunk can be processed into wood while mango kernel can be used in the saponification process since it has good quality fat.

1.1.1 Mango Fruits Botanical and Morphology Description

Mango trees are large, deeply rooted with branches that provide rounded canopy of leaves and can grow at a great height. Usually, the unripe mango skin is green or red while the ripe mango skin could be green, greenish-yellow, yellow, red or orange. The different variety of the fruit offers different physical characteristics such as shape, size, and colour, besides internal characteristics. Mango is a fleshy drupe with smooth and leathery skin (exocarp), fibrous pulp (mesocarp) and stone (endocarp) containing single seed as illustrated in Figure 1.1.

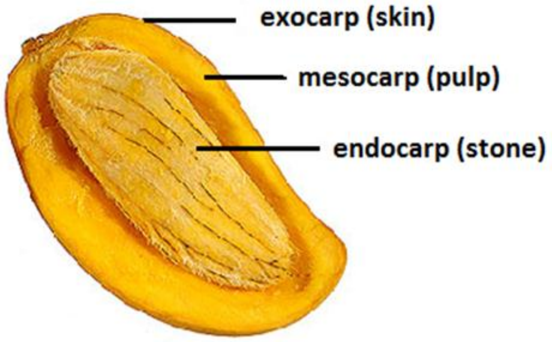

Figure 1.1: Morphology of Mango
(Source: IANS, 2014)

Chok Anan mango is the most preferred type as it is extensively and aggressively commercialized in the global market because of its' sweet taste, juicy and appealing external appearance - oval shape, tapered tip and yellow skin when ripe as shown in Figure 1.2. Because of these attributes, *Chok Anan* mango is highly favoured among the local consumers.

Figure 1.2: *Chok Anan* Mango

The range of days required for mango to mature after flowering is from 100 to 150 days. The fruit will have excellent flavour if ripen naturally on tree compared to the ones ripen using storage method (Knight, 1997). However, the natural ripening process faces critical challenges such as pest threats, fruit abnormalities and etc. Therefore, this work offers an alternative to overcome these problems by using microwave method to determine the quality of mangoes that are ripening naturally on trees.

1.2 Quality Assessment of Mango

Usually, quality is closely related to mango ripening stage. There are no specific rules on so called suitable time to harvest mango. However, there are some common rules that can be applied in harvesting the fruit. Generally, the harvesting time for mango is about 12 to 16 weeks after the anthesis. According to Luther et al. (2004), the ripening stage of mango is strongly related to the moisture content (m.c.) inside mango. This is proven based on the composition of mango as described in Section 1.1 where it has very high m.c.. Besides that, the water loss will occur for the overripe mango (Yahia, 2011). Therefore, the determination of m.c. is essential as it determines the ripening stage as well as the quality of mango. Generally speaking, there are various methods that can be used to determine m.c. in fruits, but the most accurate, fast and non-destructive method is vital. The technique to determine the m.c. in fruits will be discussed in Chapter 2.

1.3 Microwave Techniques

Microwave techniques have been used successfully for quality and condition assessment in agricultural and concrete structures since 1950s (Kraszewski, 1980; Al-Qadi et al., 1991). The use of the techniques on materials have become essential since the interest in the development of modern instrument, sensors and probes, methods and calibration techniques to detect material abnormalities using microwaves has increased (Zoughi, 1990). In the microwave region, the frequency range is from 0.3 GHz to 300 GHz and the wavelength is between 10^{-1} m and 10^{-3}m. (Liao, 1988). Microwave non-destructive technique is suitable for the use on fruits due to its advantages compared to other non-destructive evaluation (NDE) methods such as thermographic, radiographic and magnetic particle in terms of being inexpensive, contactless features (antenna), wide area scanning and high penetration depth.

The microwave parameters that are generally measured are reflection coefficients, transmission coefficients, dielectric constants, loss factors, and complex permeability in terms of frequency in microwave region and temperature. All of these measurement parameters are closely related to material properties referring to suitable modelling and calibration. Microwave techniques are divided into two classes which are 1) free-space methods that are conducted in the far-field region such as horn lens antennas and 2) closed waveguide methods that are conducted in the near-field region such as open-ended coaxial and open-ended waveguide.

1.4 Problem Statements

The demand of fruit quality assessment has increased since the industry suffers from capital lost that occurs mainly during fruit classifying process (Aulakh & Regmi, 2013). The quality of mango is greatly dependent on the internal properties such as m.c, soluble solid content (SSC) and pH (Sun et al., 2010; Butz et al., 2005). The common practice is that mango is assessed based on its external properties such as mass (*M*), width (*W*) and length (*L*). However, the *M*, *W* and *L*of mango may not truly represent its internal quality (m.c., SSC and pH) (Soltani et al., 2011). This work focus on the internal properties since the measurement of m.c. remains the prime interest in mango assessment like all agri-food produce (Ragni et al., 2006) as well as soluble solid content (SSC) and pH. In literature, many studies have reported the range of values of m.c., SSC and pH in mango after harvesting (Sosa- Morales et al., 2009; Appiah et al., 2011; Vásquez-Caicedo et al., 2002) but lack of information for mango during its developmental stages. Several measurements techniques have been proposed to determine mango quality (Ueda et al., 2001; Jha et al., 2011). The existing methods to determine the m.c., SSC and pH in mango such as conventional oven drying (Nielsen, 2010), refractometer (Kader et al., 2003) and pH meter (Kulasekaran et al., 2015) are laborious, difficult, time consuming, and destructive. Thus, this work provides an accurate, rapid, cost-effective and non-destructive technique.

Numerous literatures report on the different techniques for non-destructive analysis of food, which include acoustic, spectroscopic (Near infrared (NIR)), electrical, magnetic resonance, X-ray and computed tomography (Sun et al., 2010; Butz et al., 2005; Ruiz-Altisent et al., 2010). However, all of these techniques are bulky and laborious.

Dielectric characterisation of agri-food produce is relatively a new method (Jamaludin et al., 2014), and is emerging using the commercial Keysight open-ended coaxial probe (KOEC). The KOEC probe has been used to determine the permittivity of fruits such as palm oil (Yeow, 2006) and apple (Guo et al., 2011). The KOEC is designed for permittivity measurement of liquid and semi-solid materials. Yet, the accuracy of the permittivity measurement for solid samples has not been evaluated. In the development of mango, water plays an important role since it is the main composition in the fruit, which is from 72.7% to 88.1% from week 5 to week 17 observation. The small changes in m.c. during fruit development require the usage of a sensor with better performance in reflection measurement.

This work proposed the use of open-ended sub-miniature panel (SMA-P) coaxial sensor for the determination of m.c., permittivity, SSC and pH from week 5 to week 17 during fruit development. The determination of m.c. and permittivity in mango will be based on the measured values of reflection coefficient. Once the calibration equations have been established, the technique can be performed non-destructively. The accuracy of the technique can be determined by calculating the reflection coefficients of the samples by inserting the permittivity values in the finite element method calculation and then compared with the actual measured values using SMA-P coaxial sensor.

1.5 Research Objectives

The main objectives of this study are:

1. To determine the variation in mass, width, length, m.c., pH and SSC in mango with weeks after anthesis during fruit development.
2. To establish the relationships between dielectric constant, loss factor, critical frequency and m.c. in mango.
3. To determine the accuracy of permittivity results using finite element method (FEM) by comparing the calculated and measured results for the magnitude of reflection coefficient, $|S_{11}|$.
4. To establish the calibration equations relating $|S_{11}|$ with dielectric constant, loss factor and m.c., validate the accuracy of each calibration equations and analyse the performance of open-ended sub-miniature panel (SMA-P) coaxial sensor.

1.6 Scope of the Study

The major focus of this study is to determine the quality of mango based on m.c. parameters using the open-ended sub-miniature panel (SMA-P) coaxial sensor that is applied during growth development of *Chok Anan* mango.

Chapter 2 presents various techniques to determine the quality of fruits in general. This chapter also discusses the conventional methods to determine m.c. of fruits. This is then followed by an overview of two common microwave sensors to determine m.c. in agricultural and food products. A brief introduction to various numerical methods to calculate the reflection coefficient, $|S_{11}|$ SMA-P coaxial sensor will also be presented.

Chapter 3 highlights the theoretical background of the microwave techniques, which includes Maxwell's equations and boundary conditions. Two approaches to calculate the $|S_{11}|$ of coaxial sensor using admittance model and finite element method are also presented.

Chapter 4 describes detailed experimental procedures to obtain the mass, size, m.c., SSC and pH in mango using the standard method as well as the permittivity values of different percentage of m.c. in mango using Keysight open ended coaxial probe. In addition, this chapter also presents the procedures to obtain $|S_{11}|$ of the SMA-P coaxial sensor immersed in standard materials (water) as well as different percentage of m.c. in mango.

Chapter 5 consists of four main parts. The first part discusses about the pattern of the mass, width, length, m.c., SSC and pH in mango during fruit development from week 5 to 17. The second part presents the variation of dielectric properties (dielectric constant and loss factor) at different percentage of m.c.. The third part focuses on the comparison of measured and calculated $|S_{11}|$ using finite element method for standard materials (air and water) and different m.c. values. Apart from that, the calibration equation to predict the m.c. dielectric constant and loss factor based on $|S_{11}|$ measurements are also presented. The final part presents the discussion on the prediction of SSC and pH based on the m.c. measurement using SMA-P coaxial sensor.

Finally, Chapter 6 summarizes all the results and findings obtained in this study. This chapter also presents several recommendations for future works pertaining to this study.

REFERENCES

AACC. (2000). *Approved Methods of the American Association of Cereal Chemist* (10thed.). St. Paul, MN, USA: AACC International.

Abbas, Z., Yeow, Y. K., Shaari, A. H., Zakaria, A., Hassan, J., Khalid, K., & Saion, E. (2005a). Fast and accurate technique for determination of moisture content in oil palm fruits using open-ended coaxial sensor.*Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers*, *44*(7A), 5272–5274.

Abbas, Z., Yeow, Y. K., Shaari, A. H., Khalid, K., Hassan, J., & Saion, E. (2005b). Complex permittivity and moisture measurements of oil palm fruits using an open-ended coaxial sensor. *IEEE Sensors Journal*, *5*(6), 1281–1287.

Abbas, Z., R, Mokhtar., K, Khalid., M, Hashim., & S, Abdul Aziz. (2007). RDWG technique of determinations of moisture content in oil palm fruits.*The Europian Physical Journal Applied Pyhsics, 40*, 207-210.

Abidin, M. I. Z. (1991). *Pengeluaran Buah-buahan.* Kuala Lumpur: Dewan Bahasa dan Pustaka.

Aderinlewo, A. A., Adisa, A. F., & Salaudeen, O. (2013). Investigation of solar drying of plaintain and cassava slices under natural convection. *Journal of Experimental Research, 1*(1), 21-24.

Aina, J. O. (1990). Physico-chemical changes in African mango (Irvingiagabonensis) during normal storage ripening. *Food Chemistry*, *36*(3), 205–212.

Ali, H. H., Abbas, Z. B., Hassan, J. B., Jusoh, A. B., & Zahari, R. B. M. (2011). Microwave antenna sensing technique for determination of moisture content in hevea latex from Hevea brasiliensis tree.*Australian Journal of Crop Science*, *5*(11), 1326–1333.

Al-Qadi, I. L., Ghodgaonkar, D. K., Varadan, V. K. & Varadan, V. K. (1991). Effect of moisture on asphaltic concrete at microwave frequencie. *IEEE Transactions on Geoscience and Remote Sensing*, *29*, 710-717.

Ansarudin, F., Abbas, Z., Hassan, J., Yahaya, N. Z., & Ismail, M. A. (2012). A simple insulated monopole sensor technique for determination of moisture content in Hevea rubber latex. *Measurement Science Review*, *12*(6), 249–254.

Appiah, F., Kumah, P., & Idun, I. (2011). Effect of ripening stage on composition, sensory qualities and acceptability of Keitt mango (*Mangiferaindica L.*) chips. *African Journal of Food, Agriculture, Nutrition and Development*, *11*(5), 5096-5109.

Asiedu, J. J. (1987). Physicochemical Changes in Plantain (*Musa paradisiaca*) during Ripening and the Effect of Degree of Ripeness on Drying. *Trop. Sci., 27,*249–260.

Ashcraft, C. & Liu, J. W. H. (1998). Robust ordering of sparse matrices using multisection, *SIAM J. Matrix Analysis and Applic., 19*, 816–832.

Aulakh, J., & Regmi, A. (2013). Post-harvest food losses estimation-development of consistent methodology. *First Meeting of the Scientific Review Committee of the Food and Agricultural Organization of the UN*, 2050, 1–34.

Azlina, N., Abdul, Z., & Abdul, R. (2014). An overview of fruit supply chain in Malaysia. *Jurnal Mekanikal*, *37*, 36–46.

Bahi, J., & Couturier, R. (2011). Parallel GMRES implementation for solving sparse linear systems on GPU clusters. *Proceedings of the 19th High Performance Computing Symposia*, 12–19.

Balbontín, C., Ayala, H., Rubilar, J., Cote, J., & Figueroa, C. R. (2014). Transcriptional analysis of cell wall and cuticle related genes during fruit development of two sweet cherry cultivars with contrasting levels of cracking tolerance. *Chilean Journal of Agricultural Research, 74*(2), 162–169.

Bally, I. S. E., Lu, P., & Johnson, P. R. (2009). Mango breeding. In Jain, S. M. & Priyadarshan P. M. (Eds.), *Plantation Tree Crops: Tropical Species* (pp. 51-82). New York: Springer.

Baradey, Y., Hawlader, M. N. A., Ismail, A. F., Hrairi, M., & Rapi, M. I. (2016). Solar drying of fruits and vegetables. *International Journal of Recent Development in Engineering and Technology*, *5*(1), 1-6.

Barba A. A., & d'Amore, M. (2012). *Relevance of Dielectric Properties in Microwave Processes*. Italy: University of Salemo.

Blackham, D. V., & Pollard, R. D. (1997). An improved technique for permittivity measurement using coaxial probe. *Instrumentation and Measurement, IEEE Transaction on*, *46*(5), 1093-1099.

Booton, R. (1992). *Computational Methods for Electromagnetics and Microwaves*. New York: John Wiley and Sons.

Bouraoui, M., Richard, P., & Fichtali, J. (1993). A review of m.c. determination in foods using microwave oven drying. *Food Research International*, *26*(1), 49-57.

Brenner, S. C., & Scott, L. R. (2008). *The Mathematical Theory of Finite Element Method*. New York: Springer.

Butz, P., Hofmann, C., & Tauscher, B. (2005). Recent developments in noninvasive techniques for fresh fruit and vegetables internal quality analysis. *Journal of Food Science-Chicago*, *70* (9), 131.

Chen, L. F., Ong, C. K., Neo, C. P., Varadan, V. V., & Varadan, V. K. (2004). *Microwave Electronics Measurement and Materials Characterization*. England: John Wiley & Sons Ltd,.

Clough, R. W. (1960). The finite element method in plane stress analysis. *Proc. American Society of Civil Engineers (2nd Conference on Electronic Computation, Pitsburg, Pennsylvania), 23*, 345-378.

Collin, R. E. (1991). *Field Theory of Guided Waves*. New York: IEEE Press.

Courant, R. (1943). Variational methods for the solution of problems of equilibrium and vibrations. *Bulletin of the American Mathematical Society*, *49*, 1-23.

Dadzie, B. K., & Orchard, J. E. (1997). *Routine Post-Harvest Screening of Banana/Plantain Hybrids: Criteria and Methods* (pp. 75). Italy: International Plant Genetic Resources Institute.

Decareau, R. V. (1981). *Microwaves in the Food Processing Industry, Series of Food Science and Technology*. Academic Press: New York.

DOA. (2017). *Statistik Tanaman (Sub-Sektor Tanaman Makanan*. Malaysia: DOA

Doymaz, I. (2012). Infrared drying of sweet potato (Ipomoea batatas L.) slices. *Journal of Food Science and Technology*, *49*(6), 760–766.

Dulawat, M. S., & Rathore, N. S. (2012). Forced convection type solar tunnel dryer for industrial applications. *Agricultural Engineering International: CIGR Journal*, *14*(4), 75–79.

FAMA. (2006). *Menuju kearah Kualiti Malaysia's Best, Siri Panduan Kualiti Manga.* Malaysia: FAMA.

FAO. (2008, April 1). Banana, mango, and pineapple, leading fruit produced and traded worldwide. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=PH2009000126

Grant, J. P., Clarke, R. N., Symm, G. T. & Spyrou, N. M. (1989). A critical study of the open-ended coaxial line sensor technique for RF and microwave complex permittivity measurements. *Journal of Physics: Electronics and Scientific Instrument*, *22*, 757-770.

Guo, W., Zhu, X., Liu, Y., & Zhuang, H. (2010). Sugar and water contents of honey with dielectric property sensing. *Journal of Food Engineering*, *97*(2), 275–281.

Guo, W., Zhu, X., Nelson, S. O., Yue, R., Liu, H., & Liu, Y. (2011). Maturity effects on dielectric properties of apples from 10 to 4500 MHz. *LWT -Food Science and Technology*, *44*(1), 224–230.

Hasted, J. B. (1973). *Aqueous Dielectric*. London: Chapman and Hall.

Handoko, E., Mangasi, A. M., Iwan, S., Randa, M., & Alaydrus, M. (2017). Measurement of complex permittivity and permeability of hexagonal ferrite composite material using a waveguide in microwave band. *Proceeding - 2016 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications, ICRAMET*, 28–30.

Harrington, R. F. (1987). The method of moments in electromagnetics. *Journal of Electromagnetic Waves and Applications*, *1*(3), 181–200.

Hodge, S. (2001). The effect of pH and water content of natural resources on the development of Drosophila melanogaster larvae. Dros. *Inf. Serv,84*, 38-43.

Hwang, Y. W., Lee, H. G., & Won, T. Y. (2014). Numerical Analysis Using Finite Element Method On Phosphorescent Organic Light Emitting Diodes. *JSTS:Journal of Semiconductor Technology and Science, 14*(1), 29–33.

Ibrahim, N. U. A., Abd Aziz, S., & Nawi, N. M. (2017). Novel impedance measurement technique for soluble solid content determination of banana. *Pertanika J. Sci. & Technol, 25* (2), 519 – 526.

Ibrahim, N. M. (2015). *Fiber Optic Technique for Determination of Moisture Content in Honey.* Msc Thesis, Universiti Putra Malaysia.

Ikediala, J. N., Tang, J., Drake, S. R., & Neven, L. G. (2000).Dielectric properties of apple cultivars and codling moth larvae. *American Society of Agricultural Engineers*, *43*(5), 1175-1184.

IANS. (2014, July 22). Indian scientists develop seedless mangoes [Blog post]. Retrieved from http://mangoworldmagazine.blogspot.my/2014/07/indian-scientists-develop-seedless.html

Isengard, H. D. (1995). Rapid water determination in foodstuffs. *Trends in Food Science and Technology*, *6*(5), 155-162.

Ito, T., Sasaki, K., & Yoshida, Y. (1997). Changes in respiration rate, saccharide and organic acid content during the development and ripening of mango fruit (Mangiferaindica L. ‘Irwin’) cultured in a plastic house. *Journal of the Japanese Society for Horticultural Science*, *66*(3-4), 629–635.

Jamaludin, D., Abd Aziz, S., & Ibrahim, N. U. A. (2014). Dielectric based sensing system for banana ripeness assessment. *International Journal of Environmental Science and Development*, *5*(3), 286-289.

Jancarik, J., & Kim, S. H. (1991). Sparse matrix sampling.A screening method for crystallization of proteins. *Journal of Applied Crystallography*, *24*(pt 4), 409–411.

Jha, S. N., Narsaiah, K., Basediya, A. L., Sharma, R., Jaiswal, P., Kumar, R., & Bhardwaj, R. (2011). Measurement techniques and application of electrical properties for nondestructive quality evaluation of foods-a review. *Journal of Food Science and Technology*, *48*(4), 387-411.

Jiao, D., & Jin, J. M. (1999). Fast- frequency sweep analysis of microstrip antennas on dispersive substrate. *Electronics Letters*, *35*(14), 1122-1123.

Jin, J. M., & Volakis, J. L. (1991). Electromagnetic scattering by and transmission through a three-dimensional slot in a thick conducting plane. *Antennas and Propagation, IEEE Transaction on*, *39*(4), 543-550.

Jin, J. M., & Volakis, J. L. (1991). A hybrid finite element method for scattering and radiation by microstrip patch antenna and arrays residing in a cavity. *IEEE Transactions on Antennas and Propagation*, *39*(11), 1598-1604.

Jin, J. M., & Jin, J. (2002). *The Finite Element Method in Electromagnetics*. New York: Wiley.

Jusoh, M.A., Abbas, Z., Hassan, J., Azmi, B.Z., Ahmad, A.F. (2011). A simple procedure to determine complex permittivity of moist materials using standard commercial coaxial sensor. *Measurement Science Review*, *11*(1), 19-22.

Kaatze, U. (2005). Electromagnetic wave interactions with water and aqueous solutions.In Kupfer, K. (Eds.), .*Electromagnetic Aquametry*. Berlin: Springer Verlag.

Kaatze, U., Kupfer, K., & Hübner, C. (2007). Microwave Moisture Measurements. *Measurement Science and Technology*, *18*(4).

Kader, A., Hess-Pierce, B., & Almenar, E. (2003). Relative contribution of fruit constituents to soluble solids content measured by a refractometer. *Hortscience*, 38(5), 833.

King, R. W. P., Lee, K. M., Mishra, S. R., & Smith, G. S. (1973). Insulated linear antenna: theory and experiment. *J Appl Phys*, *45*(4), 188-1697.

Kittur, F., Saroja, N., Habibunnisa., & Tharanathan, R. N. (2001). Polysaccharide-based composite coating formulations for shelf-extension of fresh banana and mango. *European Food Research and Technology*, *213*(4), 306–311.

Knight, R. J. (1997). *Important Mango Cultivars and Their Descriptors*. Homestead, Florida, USA: Tropical Research and Education Centre, University of Florida.

Kraszewski, A. (1980). Microwave Aquametry. *10th European Microwave Conference*, 48–58.

Kraszewski, A. W., Nelson, S. O., & You, T. S. (1991). Moisture content determination in single corn kernels by microwave resonator techniques. *Journal of Agricultural Engineering Research*, *48*(C), 77–87.

Kraszewski.A. (2001). Microwave aquametry : An effective tool for nondestructive moisture sensing. *Subsurface Sensing Technologies and Applications, 2*(4), 347-362.

Kulasekaran, A., Andal, G., Lakshimipathy, R., & John Alexander, J. (2015). Modification in pH measurements for getting accurate pH values with different pH meters irrespective of aging and drifts in the meters. *International Journal of ChemTech Research, 8*(5), 16–24.

Kupfer, K. (2005). *Electromagnetic Aquametry.* Germany: Springer.

Lam, P. F., Ng, K. H., Omar, D., & Talib, Y. (1982). *Physical, Physiological and Chemical Changes of Golek After Harvest*. Philippines: ASEAN Postharvest Training College, Laguna.

Lammertyn, J., Dresselaers, T., Van Hecke, P., Jancsók, P., Wevers, M., & Nicolai, B. M. (2003b). MRI and X-ray CT study of spatial distribution of core breakdown in 'Conference' pears. *Magn.Reson. Imaging, 21*, 805-815.

Lamsal, B. P., & Jindal, V. K. (2014).Variation in electrical conductivity of selected fruit juices during continuous Ohmic heating. *International Journal of Applied Science and Technology*, *7*(1), 47-56.

Leemans, V., & Destain, M. F. (2004). A real-time grading method of apples based on features extracted from defects. *J. Food Eng., 61*, 83–89.

Leghari, M. H., Ahmed, S. S., Meman, N. U. N., Soomro, A. H., & Khooharo, A. A. (2013). Quality attributes of immature fruit of different mango varieties. *Journal of Basic & Applied Sciences*, *9*, 52-56.

Léchaudel, M., & Joas, J. (2007). An overview of preharvest factors influencing mango fruit growth, quality and postharvest behaviour. *Brazilian Journal of Plant Physiology, 19*(4), 287-298.

Li, C. L., & Chen, K. M. (1995). Determination of electromagnetic properties of materials using flanged open-ended coaxial probe–Full-wave analysis. *IEEE Trans. Instrum. Meas., 44*, 19–26.

Liao, S. Y. (1988). Engineering Application of Electromagnetic Theory, St. Paul: West Publishing Company.

Lu, R. (2003). Detection of bruises on apples using near-infrared hyperspectral imaging. *Trans. ASAE*, *46*, 523–530.

Lucas, E. W., & Fontana, T. P. (1995). A 3-D hybrid finite element/boundary element method for the unified radiation and scattering analysis of general infinite periodic array. *Antennas and Propagation, IEEE Transaction on*, *43*(2), 145-153.

Luther, R., Dwayne, A., & Gerald, H. (2004).*Food & Process Engineering Technology*. St. Joseph Michigan: ASAE.

Marin, S. P. (1982). Computing scattering amplitudes for arbitrary cylinders under incident plane waves. *IEEE Trans. Antennas Propagat., 30*, 1045–1049.

Marsland, T. P., & Evans, S. (1987). Dielectric measurements with an open-ended coaxial probe. *IEE Proceedings H Microwaves, Antennas and Propagation, 134*(4), 341–349.

Mei, K. E. (1974). Unimoment method of solving antenna and scattering problems. *IEEE Transactions on Antennas and Propagation*, 760-766.

Mendoza, D. B. (1981).*Development Physiology of 'Carabao' Mango* (*Mangifera indica L.)* fruits. PhD Thesis.University of the Philippines, College.

Mudgett, R. E. (1986). Electrical properties of foods. In Rao, M. A., & Rizvi, S. S. H. (Eds.), *Engineering properties of foods* (pp. 329–390). New York: CRC Press.

Method, F. T., Duan, Y.-T., Chen, B., Fang, D., & Zhou, B.-H.(2011). Efficient Implementation for 3-D Laguerre-Based Finite-Difference Time-Domain Method. *IEEE Transactions on Microwave Theory and Techniques, 59*(1), 56–64.

Nanthachai, P. (1982). *Fruit Moprpohology and Development in Mango* (*Mangifera indica L.*). Philippines: ASEAN Postharvest Training College, Laguna.

Nelson, S., Forbus, W. J., & Lawrence, K. (1994). Permittivities of fresh fruits and vegetables at 0.2 to 20 GHz. *Journal of Microwave Power and Electromagnetic Energy*, *29*(2), 81–93.

Nelson, S. O., Trabelsi, S., & Kays, S. J. (2008). Dielectric Spectroscopy of Melons for Potential Quality Sensing. *American Society of Agricultural and Biological Engineers*, *51*(6), 2209–2214.

Nielsen, S. S. (2010). *Food Analysis*.4th Edition. USA: Springer

Norimi, A. M., Abbas, Z., Jusoh, A., & Ismail, M. A. (2012). Determination of moisture content of maize kernel (Zea mays L.) by reflectance measurement at wavelengths 300nm to 800nm using optical technique. *PIERS Proceedings*, 1072–1074.

Nowak, D., & Lewicki, P. P. (2004). Infrared drying of apple slices. *Innovative Food Science and Emerging Technologies*, *5*(3), 353–360.

NPTEL. (2009, December 31). Boundary conditions for electromagnetic field [Blog post]. Retrieved from http://nptel.ac.in/courses/117103065/36.

Nyfors, E., & Vainikainen, P. (1991). Industrial Microwave Sensors. *IEEE MTT-S International Microwave Symposium Digest*, *3*, 1009-1012.

Opara, U. L., Al-Ani, M. R., & Al-Rahbi, N. M. (2012). Effect of fruit ripening stage on physico-chemical properties, nutritional composition and antioxidant components of tomato (Lycopersicum esculentum) cultivars. *Food and Bioprocess Technology*, *5*(8), 3236–3243.

Padda, M. S., Amarante, C. V. T., Garciac, R. M., Slaughter, D. C., & Mitchama, E. J. (2011). Methods to analyzephysico-chemical changes during mango ripening: A multivariate approach. *Postharvest BiolTechnol,62*, 267-74.

Palmer, J. (1995). Attention in visual search: Distinguishing four causes of a set-size Effect. *Current Directions in Psychological Science*, *4*(4), 118–123.

Pleguezuelo, C. R. R., Zuazo, V. H. D., Fernandez, J. L. M., & Tarifa, D. F. (2012). Physico-chemical quality parameters of mango (Mangiferaindica L.) fruits grown in a Mediterranean subtropical climate (SE Spain). *J AgriSci Tech,14*, 365-74.

Quintana, E.G., Nanthachai, P., Hiranpradit, H., Mendoza Jr, D. B., & Ketsa, S. (1984). Changes in mango during growth and maturation: Growth and development of mango. In Mendoza, D. B., Wills, R. B. H. (Eds.), *Mango Fruit Development, Postharvest Physiology and Marketing in ASEAN* (pp. 21–27). Kuala Lumpur: ASEAN Food Handling Bureau.

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,94*, 255-262.

Ritz, W. (1909).Über eine Neue Metode zur Lösung gewisser Variations probleme der Matematischen Physik. *J. Reine Angew. Math*., *135*, 1-61.

Ruiz-Altisent, M., Ruiz-Garcia, L., Moreda G. P., Lu, R., Hernandez-Sanchez, N., Correa, E. C., Diezma, B., Nicolai, B., & Garcia-Ramos, J. (2010). A review of sensors for product characterization and quality of speciality crops. *Computers and Electronics in Agriculture*, *74* (2), 176-194.

Ryynanen, S. (1995). The electromagnetic properties of food materials: A review of basic principles. *Journal of Food Engineering*, *27*(4), 409-429.

Sadiku, M. N. (2001). *Elements of Electromagnetism*. New York: Oxford University Press.

Santhirasegaram, V., Razali, Z., George, D. S., & Somasundram, C. (2015). Comparison of UV-C treatment and thermal pasteurization on quality of *Chok Anan* mango (Mangiferaindica L.) juice. *Food and Bioproducts Processing*, *94,* 313–321.

Schirmer, P., Janjai, S., Esper, A., Smitabhindu, R., & Mühlbauer, W. (1996). Experimental investigation of the performance of the solar tunnel dryer for drying bananas. *Renewable Energy*, *7*(2), 119–129.

Serdyuk, V. M. (2008). Dielectric study of bound water in grain at radio and microwave frequencies. *Progress In Electromagnetics Research, PIER, 84,* 379–406.

Shanmuganantham, T., Raghavan, S., & Sriram Kumar, D. (2007). Comparison of numerical techniques for rectangular microstrip patch antenna. *IEEE Conference on Electron Devices and Solid-State Circuits 2007, EDSSC 2007*, 247–250.

Schenk, O., & Ğartner, K. (2004). Solving unsymmetric sparse systems of linear equations with PARDISO. *In Future Generation Computer Systems, 20*, 475–487.

Shofian, N. M., Hamid, A. A. B., Osman, A., Saari, N., Anwar, F. C., Dek, M. S. P., & Hairuddin, M. R. (2011). Effect of freeze-drying on the antioxidant compounds and antioxidant activity of selected tropical fruits. *International Journal of Molecular Sciences*, *12*(7), 4678–4692.

Silvester, J., & Ferrari, R. L. (1996). *Finite Elements for Electrical Engineers*. England: Cambridge University Press.

Slaughter, S. (1995). Non-destructive determination of internal quality in peaches and nectarines. *Trans. ASABE, 38*,617-623.

Soloman George, D., Razali, Z., & Somasundram, C. (2016). Physiochemical Changes during Growth and Development of Pineapple (Ananas comosus L. Merr. cv. Sarawak). *J. Agr. Sci. Tech, 18*, 491–503.

Soltani, M., Alimardani, R., & Omid, M. (2011). Use of dielectric properties in quality measurement of agricultural products. *Nature and Science*, *9*(4), 57-61.

Sosa-Morales, M.E., Tiwari, G., Wang, S., Tang, J., Gancia, H. S. & Lopez-Malo, A. (2009). Dielectric heating as a potential post-harvest treatment of disinfesting mangoes, Part I: Relation between dielectric properties and ripening. *Biosystems Engineering,103*, 297-303.

Sousa de Brito, E., & Narain, N. (2002). Physical and chemical characteristics of sapota fruit at different stages of maturation. *Pesquisa Agropecuaria Brasileira, 37*(4), 567–572.

Spreer, W., & Müller, J. (2011). Estimating the mass of mango fruit (Mangifera indica, cv. Chok Anan) from its geometric dimensions by optical measurement. *Computers and Electronics in Agriculture*, *75*(1), 125–131.

Sun, T., Huang, K., Xu, H., & Ying, Y. (2010). A review of research advances in non-destructive determination of internal quality in watermelon/melon. *J. Food Eng, 100*(4), 569-577.

Ueda, M., Sasaki, K., Utsunomiya, N., Inaba, K., Shimabayashi, Y. (2001). Effect of temperature and time on some properties during storage of mango fruit

(Mangifera indica L. ‘Irwin’) cultured in plastic house. *J Japan Soc Food Sci Technol*, 48(5), 349–355

Thumm, M., Wiesbeck, W., Note, A., Huisman, J. a., Thakur, O. P., Singh, A. K., & Authority, S. (2012). The relationship between loss, conductivity, and dielectric constant. *Advanced Studies in Theoretical Physics*, *46*(5), 1–12.

Tiris, C., Tiris, M., & Dincer, I. (1996). Experiments on a new small-scale solar dryer. *Applied Thermal Engineering*, *16*(2), 183–187.

Vásquez-Caicedo, A. L., Neidhart, S., Pathomrungsiyounggul, P., Wiriyacharee, P., Chattrakul, A., Sruamsiri, P., Manochai, P., Bangerth, F., & Carle, R. (2002). Physical, chemical and sensory properties of nine Thai mango cultivars and evaluation of their technological and nutritional potential. *International Symposium Sustaining Food Security and Managing Natural Resources in Southeast Asia*, 1-13.

Vesali, F., Gharibkhani, M., & Komarizadeh, M.H. (2011). An approach to estimate moisture content of apple with image processing method**.** *Australian Journal of Crop Science*, *5*(2), 111-115.

Ventakesh, M. S., & Raghavan, G. S. V. (2004). An overview of microwave processing and dielectric properties of agri-food materials. *Biosystems Engineering, SilsoeResearch Institute, Elsvier Lt,88*(1), 1-18.

Wongmetha, O., Ke, L. S., & Liang, Y. S. (2015). The changes in physical, bio-chemical, physiological characteristics and enzyme activities of mango cv. Jinhwang during fruit growth and development. *NJAS - Wageningen Journal of Life Sciences, 72*, 7–12.

Yahaya, Z. (2013). *Development of Simple Rectangular Microstrip Sensor for Determination of Moisture Content of Hevea Rubber Latex.* PhD Thesis, Universiti Putra Malaysia.

Yahia, E. M. (2011). *Postharvest Biology and Technology of Tropical and Subtropical Fruits*. United Kingdom: Woodhead Publishing Limited.

Yeow, Y. K. (2006). *A critical Study of Open- Ended Coaxial Sensor for Oil Palm Fruits Measurements.* PhD Thesis, Universiti Putra Malaysia.

Yeow, Y. K., Abbas, Z., & Khalid, K. (2010). Application of microwave moisture sensor for determination of oil palm fruit ripeness. *Measurement Science Review*, *10*(1), 7–14.

Zainuddin, M. F., Abbas, Z., Hafizi, M. H. M., Jusoh, M. A., & Hj Razali, M. H. (2013). Monopole antenna technique for determining moisture content in the Dioscorea hispida tubers. *Australian Journal of Crop Science*, *7*(1), 1–6.

Zoughi, R. (1990). Microwave non-destructive testing: Theories and applications.In *International Advances in Nonestructive Testing*. United States: Gordon and Breach Publishers Inc..