MICROWAVE EXTRACTION OF ESSENTIAL OILS FROM ‘PENAGA LILIN’ (MESUA FERREA L.) LEAVES

RUDY NURDIN

FS 2007 53
MICROWAVE EXTRACTION OF ESSENTIAL OILS FROM ‘PENAGA LILIN’ (MESUA FERREA L.) LEAVES

By

RUDY NURDIN

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

September 2007
DEDICATION

Specially dedicated to:

My Mother,
My Brothers,
My Sisters,
My Cousins,
My Friends,
My Lecturers
for their encouragement and support.
Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

MICROWAVE EXTRACTION OF ESSENTIAL OILS FROM ‘PENAGA LILIN’ (MESUA FERREA L.) LEAVES

By

RUDY BIN NURDIN

September 2007

Chair : Kaida bin Khalid, PhD

Faculty : Science

The purpose of this research is to compare the performance of the Microwave Extraction Technique (MET) with the Conventional Extraction Technique (CET) in extracting an essential oils from Mesua ferrea L. leaves using various methods such as dry distillation (DD), wet distillation (WD), hydro distillation (HD) and steam distillation (SD) in terms of its rapidity and efficiency to extract the quality percentage of yield and chemical composition of essential oil. The important extraction process parameters, i.e, time, temperature and microwave power output are controlled to obtain the highest quantity and quality of essential oil rapidly. The MET is performed using DD and WD at irradiation power of about 450 W and temperature about 100°C for 1 hour whereas CET is performed using HD and SD at extraction power of 450 W and temperature 100°C for 8 hours. The absorption power of microwave irradiation by Mesua ferrea L. leaves are also estimate for DD and WD. This is to determine which method gives higher value of absorption power. By estimating the absorption power in order to know which method is more efficient in heating process. The MET provides a rapid extraction, with about 8 times faster than
CET. After 1 hour of MET, it is possible to collect sufficient essential oil which provides comparable yields to those obtained 8 hours using CET. From 200 g actual weight of leaves, during HD gives the highest yield of extracted essential oil with 0.057% of weight compared to WD with 0.039% whereas DD gives 0.031% and SD which provides the least yield contributes 0.021%. Although more compounds are detected in the essential oil extracted by CET, substantial higher amounts of highly odoriferous compounds are present in the MET extract. During MET, DD requires only 5 minutes to obtain its first essential oil droplet and WD requires 19 minutes whereas during CET, both HD and SD requires 27 and 36 minutes, respectively. DD requires less time to obtain its first oil droplet compared to the other methods due to higher absorption power for dry sample than for wet sample. It is found that the absorption power in DD is 3 times higher with $4.2 \times 10^6 \text{W/m}^3$ compared to WD with only $1.5 \times 10^6 \text{W/m}^3$. This is due to higher electric field strength inside the dry sample with $2.7 \times 10^4 \text{V/m}$ compared to the wet sample with $2.0 \times 10^3 \text{V/m}$. This shows that MET is 70% more efficient in heating proses compared to CET only 50%. In terms of the power output consumed for 1 hour of MET and 8 hours of CET, DD requires the least energy with 12 kW whereas WD requires 17 kW while both HD and SD consume higher energy 216 kW. This shows that energy can be saved about 13 to 18 times using MET. In terms of the economical aspect, the MET is cost saving compared to CET. The rate of cost energy consumption for the extraction cost during MET for both DD and WD performed for 8 hours are RM 3.71 and RM 5.23, respectively whereas during CET, both HD and SD involve an extraction cost of RM 11.77, respectively. This shows that about RM 6.54 to RM 8.06 can be saved by using MET. The project successfully proved the MET is an alternative technique for
the extraction of essential oils from plant materials like leaves. Essentially, the MET provides an easily controlled system, rapid and safe extraction process; high yield and purity extracts, more valuable and good quality of essential oils, extracts with chemical compositions comparable to conventional method and allows a substantial saving of energy. These advantages not only reduce operating costs, but also result in a more environmental friendly extraction process.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

GELOMBANG MIKRO MENGEKSTRAK MINYAK PATI DARIPADA DAUN ‘PENAGA LILIN’ (MESUA FERREA L.)

Oleh

RUDY BIN NURDIN

September 2007

Pengerusi : Kaida bin Khalid, PhD

Fakulti : Sains

Tujuan penyelidikan ini adalah untuk membandingkan prestasi Teknik Pengekstrakan Gelombang Mikro (MET) dengan prestasi Teknik Pengekstrakan Biasa (CET) dalam mengekstrak minyak pati daripada daun Mesua ferrea L. menggunakan pelbagai kaedah seperti penyulingan kering (DD), penyulingan basah (WD), penyulingan hidro (HD) dan penyulingan wap (SD) dari segi kecepatan dan kecekapannya dalam mengekstrak peratusan dan komposisi kimia minyak pati yang berkualiti. Kawalan parameter-parameter penting proses pengekstrakan seperti masa, suhu dan kuasa output gelombang mikro telah dilaksanakan bagi memperolehi hasil ekstrak minyak pati pada tahap tertinggi dari segi kuantiti dan kualiti secepat yang mungkin. MET dijalankan menggunakan DD dan WD pada kuasa sinaran 450 W dan suhu sekitar 100°C selama 1 jam manakala CET dijalankan menggunakan HD dan SD pada kuasa pengekstrakan 450 W dan suhu 100°C selama 8 jam. Perkiraan kuasa serapan sinaran gelombang mikro oleh daun Mesua ferrea L. semasa DD dan WD juga lakukan. In bertujuan menentukan kaedah manakah akan memberikan nilai kuasa serapan tertinggi. Dengan perkiraan kuasa serapan tersebut, dapat diketahui

vi
kaedah yang lebih efisien dalam proses pemanasan. MET membekalkan pengekstrakan yang cepat, lebih kurang 8 kali lebih cepat berbanding CET. Selepas 1 jam MET, ianya cukup memungkinkan memperolehi sejumlah minyak pati yang dapat membekalkan hasil ekstrak yang setara berbanding 8 jam pengekstrakan menggunakan CET. Daripada berat asal daun iaitu 200 g, semasa HD memberikan hasil ekstrak minyak pati yang tertinggi dengan 0.057% daripada berat asal berbanding WD dengan 0.039% sementara DD memberikan 0.031% dan SD memberikan hasil ekstrak paling sedikit 0.021%. Walaupun banyak sebatian dikesan dalam minyak pati hasil estrak CET, namun diperlihatkan lebih banyak sebatian wangian dalam hasil ekstrak MET. Semasa MET, DD hanya memerlukan 5 minit bagi memperolehi titisan minyak pati pertama dan WD memerlukan 19 minit manakala semasa CET, kedua-dua HD dan SD masing-masing memerlukan 27 dan 36 minit. DD mengambil masa singkat bagi memperolehi titisan minyak pertama berbanding kaedah-kaedah lain kerana kuasa serapan bagi sampel kering lebih tinggi daripada kuasa serapan bagi sampel basah. Didapati bahawa kuasa serapan dalam DD adalah 3 kali lebih tinggi iaitu $4.2 \times 10^6 \text{W/m}^3$ berbanding dalam WD dengan hanya $1.5 \times 10^6 \text{W/m}^3$. Ini disebabkan kekuatan medan elektrik dalam sampel kering lebih tinggi iaitu $2.7 \times 10^4 \text{V/m}$ berbanding dengan sampel basah iaitu $2.0 \times 10^3 \text{V/m}$. Ini memperlihatkan bahawa MET adalah 70% lebih cekap dalam proses pemanasan berbanding CET hanya 50%. Dari segi kuasa output yang digunakan bagi 1 jam MET dan 8 jam CET, DD memerlukan paling sedikit tenaga iaitu 12 kW manakala WD memerlukan 17 kW sementara kedua-dua HD dan SD masing-masing menggunakan lebih tenaga iaitu 216 kW. Ini menunjukkan tenaga dapat dijimatkan 13 hingga 18 kali menggunakan MET. Dari segi aspek ekonomi, MET lebih
menjimatkan kos berbanding CET. Kos kadar penggunaan tenaga proses pengekstrakan semasa MET bagi kedua-dua DD dan WD yang dilaksanakan selama 8 jam adalah masing-masing RM 3.71 dan RM 5.23, manakala semasa CET, kedua-dua HD dan SD masing-masing melibatkan kos pengekstrakan sebanyak RM 11.77. Ini menunjukkan bahawa sebanyak lebih kurang RM 6.54 hingga RM 8.06 dapat dijimatkan dengan menggunakan MET. Projek ini telah membuktikan dengan jayanya bahawa MET merupakan suatu teknik alternatif bagi proses pengekstrakan minyak pati daripada tumbuh-tumbuhan seperti daun. Pada amnya, MET merupakan suatu sistem yang amat mudah dikawal, mengekstrak dengan pantas dan selamat, mengesktrak minyak pati yang lebih banyak, tulen dan berkualiti tinggi serta komposisi minyak yang setara dengan CET dan juga memberikan penjimatan tenaga yang banyak. Kelebihan-kelebihan ini bukan sahaja menjimatkan kos malah menyumbangkan kepada suatu proses pengekstrakan yang lebih mesra alam.
ACKNOWLEDGEMENTS

First and foremost, Alhamdulillah, All praise is due to Allah, the Lord of the Worlds, who has given me the strength and patience to finish this Masters degree until the very end. I would like to dedicate my utmost gratitude to my beloved supervisor who is also the chair of the supervisory committee, Professor Dr. Haji Kaida bin Khalid for his insight and guidance throughout the progression of my studies and the preparation of my dissertation. Without his infinite knowledge, this dissertation would not have been possible. I would especially like to thank my co-supervisors, Associate Professor Dr. Haji Aspollah Haji Md. Sukari and Associate Professor Dr. Zainal Abidin Talib for their invaluable thoughts, attentive suggestions and unlimited support throughout the study. I would like to thank University’s Research Park (TPU) for supplying the sample. I would also like to thank all the lecturers and staff of the Physics Department, UPM especially the Applied Electromagnetic Lab staff, Encik Roslim, and Encik Zulkifli and also staff of the Chemisty Department especially Encik Abbas, Encik Ishar and Encik Zainal for their various encouragement or practical help in other ways. My heartfelt gratitude to my fellow colleagues who had helped me throughout this project especially my special friend, Nurshahidah Osman for her invaluable help and co-operation in sharing ideas and information concerning my dissertation. I feel extremely blessed to have had the friendship and support of many people throughout my graduate studies. Last but not least, I would like to thank my family especially my beloved mother, Paridah binti Sunusi for her prayers and blessings, her love and support to me, her sacrifices and understanding from the very beginning of my work until my master studies were completed. I pray, May Allah reward them all the best of rewards in the Hereafter.
I certify that an Examination Committee has met on 6 September 2007 to conduct the final examination of Rudy bin Nurdin on his Master of Science thesis entitled “Microwave Extraction of Essential Oils from ‘Penaga Lilin’ (Mesau ferrea L.) Leaves” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulation 1981. The Committee recommends that the student be awarded the degree of Master of Science.

Members of the Examination Committee were as follows:

Mohd. Maarof H.A. Moksin, PhD
Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Jumiah Hassan, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Internal Examiner)

W. Mahmood Mat Yunus, PhD
Professor
Faculty of Science
Universiti Putra Malaysia
(Internal Examiner)

Ramli Abu Hassan, PhD
Professor
Faculty of Science
Universiti Teknologi Malaysia
(External Examiner)

______________________________
HASANAH MOHD. GHAZALI, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia
Date: 17 December 2007
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:

**Kaida Khalid, PhD**
Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

**Zainal Abidin Talib, PhD**
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

**Mohd. Aspollah Md. Sukari, PhD**
Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

________________________

**AINI IDERIS, PhD**
Professor and Dean
School of Graduates Studies
Universiti Putra Malaysia

Date: 22 January 2008
DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putera Malaysia or at any other institution.

___________________

RUDY NURDIN

Date: 1 November 2007
### TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>DEDICATION</strong></td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td><strong>ABSTRACT</strong></td>
<td>iii</td>
</tr>
<tr>
<td></td>
<td><strong>ABSTRAK</strong></td>
<td>vi</td>
</tr>
<tr>
<td></td>
<td><strong>ACKNOWLEDGEMENTS</strong></td>
<td>ix</td>
</tr>
<tr>
<td></td>
<td><strong>APPROVAL</strong></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td><strong>DECLARATION</strong></td>
<td>xii</td>
</tr>
<tr>
<td></td>
<td><strong>LIST OF TABLES</strong></td>
<td>xvii</td>
</tr>
<tr>
<td></td>
<td><strong>LIST OF FIGURES</strong></td>
<td>xix</td>
</tr>
<tr>
<td></td>
<td><strong>LIST OF ABBREVIATIONS</strong></td>
<td>xxvi</td>
</tr>
<tr>
<td><strong>CHAPTER</strong></td>
<td><strong>INTRODUCTION</strong></td>
<td>1-1</td>
</tr>
<tr>
<td>1</td>
<td>1.1 Introduction</td>
<td>1-1</td>
</tr>
<tr>
<td></td>
<td>1.2 Essential Oils</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td>1.3 Manufacturing of Essential Oils</td>
<td>1-5</td>
</tr>
<tr>
<td></td>
<td>1.4 Microwave Extraction Technique</td>
<td>1-8</td>
</tr>
<tr>
<td></td>
<td>1.5 Research Objectives</td>
<td>1-12</td>
</tr>
<tr>
<td></td>
<td>1.6 Index of Thesis</td>
<td>1-13</td>
</tr>
<tr>
<td>2</td>
<td><strong>THEORY</strong></td>
<td>2-15</td>
</tr>
<tr>
<td></td>
<td>2.1 Introduction</td>
<td>2-15</td>
</tr>
<tr>
<td></td>
<td>2.2 Microwave Fundamental</td>
<td>2-15</td>
</tr>
<tr>
<td></td>
<td>2.3 Microwave Generator</td>
<td>2-16</td>
</tr>
<tr>
<td></td>
<td>2.4 Wave Propagation and Complex Permittivity of Materials</td>
<td>2-17</td>
</tr>
<tr>
<td></td>
<td>2.5 Interaction between Microwaves and Materials</td>
<td>2-21</td>
</tr>
<tr>
<td></td>
<td>2.6 Dielectric Material and Electric Polarizability</td>
<td>2-25</td>
</tr>
<tr>
<td></td>
<td>2.7 Microwave Heating Mechanisms</td>
<td>2-27</td>
</tr>
<tr>
<td></td>
<td>2.8 Dipole or Orientation Interaction</td>
<td>2-29</td>
</tr>
<tr>
<td></td>
<td>2.9 Atomic and Ionic Interaction</td>
<td>2-30</td>
</tr>
<tr>
<td></td>
<td>2.10 Drying Process inside the Microwave Oven Cavity</td>
<td>2-31</td>
</tr>
<tr>
<td></td>
<td>2.11 Dielectric Mixture Model</td>
<td>2-34</td>
</tr>
<tr>
<td></td>
<td>2.12 Moisture Content of Sample</td>
<td>2-36</td>
</tr>
<tr>
<td></td>
<td>2.13 Density of Sample</td>
<td>2-38</td>
</tr>
<tr>
<td></td>
<td>2.14 Absorption Power</td>
<td>2-39</td>
</tr>
<tr>
<td></td>
<td>2.15 Microwave Oven Energy Efficiency</td>
<td>2-40</td>
</tr>
<tr>
<td></td>
<td>2.16 Estimation of Absorption Power of Fresh Leaves of the Mixture, ((P_A/\text{Vol})_{w(mk)}) during DD and WD in MET</td>
<td>2-41</td>
</tr>
<tr>
<td></td>
<td>2.16.1 Input data</td>
<td>2-42</td>
</tr>
<tr>
<td></td>
<td>2.16.2 Power output of microwave oven, ((P_A/\text{Vol})_w) during MET</td>
<td>2-42</td>
</tr>
</tbody>
</table>
2.16.3 Dielectric properties of water, $\varepsilon_w^*$ at specific frequency ($0.13 \text{ GHz}<f=2.45 \text{ GHz}<20 \text{ GHz}$) and temperature ($26^\circ\text{C}<T_w=90^\circ\text{C}<100^\circ\text{C}$)

2.16.4 Electric field strength inside of microwave oven cavity, $E_{\text{in(cavity)}} = E_{\text{in(w)}}$ during MET

2.16.5 Dielectric properties of fresh leaves mixture, $\varepsilon_{mfl}^*$

2.16.6 Volume fraction of air during DD, $V_a$ and volume fraction of water during WD, $V_w$ in MET

2.16.7 Dielectric properties of fresh leaves mixture during DD and WD, $\varepsilon_{mfl,DD}^*$ and $\varepsilon_{mfl,WD}^*$ in MET

2.16.8 Electric field strength inside fresh leaves mixture during DD and WD, $E_{\text{in(mfl,DD)}}$ and $E_{\text{in(mfl,WD)}}$ in MET

2.16.9 Absorption power inside of fresh leaves mixture during DD and WD, $(PA/Vol)_{\text{in(mfl,DD)}}$ and $(PA/Vol)_{\text{in(mfl,WD)}}$ in MET

2.16.10 New absorption power inside of fresh leaves mixture during DD and WD, $(PA/Vol)_{\text{in(mfl,DD)}}$ and $(PA/Vol)_{\text{in(mfl,WD)}}$ in MET

2.17 Power Measurement Technique

3 MATERIALS AND METHODOLOGY

3.1 Introduction

3.2 Task I - Sample preparation method

3.3 Task II - Sample characterization

3.3.1 Moisture content of fresh *Mesua ferrea* L. leaves, $MC_{fl}$ determination method

3.3.2 Dry and wet density of *Mesua ferrea* L. leaves, $\rho_{fl}$ and $\rho_{fl}$ determination method

3.3.3 Dielectric properties of water, fresh and dry *Mesua ferrea* L. leaves, $\varepsilon_w^*$, $\varepsilon_f^*$ and $\varepsilon_{dfl}^*$ (experimental method)

3.4 Task III - *Mesua ferrea* L. leaves Essential oils extraction

3.4.1 Materials for *Mesua ferrea* L. leaves essential oils extraction
3.4.2 Setup for *Mesua ferrea* L. leaves essential oils extraction 3-74
3.4.3 *Mesua ferrea* L. leaves Essential oils extraction procedure 3-77

3.5 Task IV - *Mesua ferrea* L. leaves Essential Oils quality and quantity identification 3-84
3.5.1 Gas Chromatography (GC) or Gas Chromatography-Mass Spectrometry (GC-MS) standard identification method 3-84

3.6 Task V - Power output of heating source, 
\[ PO = PA_w = (PA/\text{Vol})_w \] by water heating process measurement 3-85
3.6.1 Water heating process procedure 3-87

3.7 Experimental Errors 3-90

4 RESULTS AND DISCUSSION 4-92
4.1 Introduction 4-92
4.2 Result I - Determining the Absorption Power of Fresh Leaves Mixture during MET using DD and WD 4-93
4.2.1 Moisture Content of Fresh *Mesua ferrea* L. Leaves, \( MC_{fL} \) 4-93
4.2.2 Dry and Wet Density of *Mesua ferrea* L. Leaves, \( \rho_{dL} \) and \( \rho_{fL} \) 4-94
4.2.3 Volume Fraction of Water in Fresh *Mesua ferrea* L. Leaves Mixture, \( V_{w_{fL}} \); Volume Fraction of Air, \( V_a \) during DD and Volume Fraction of Water, \( V_w \) during WD 4-96
4.2.4 Dielectric Properties of Water, Fresh and Dry *Mesua ferrea* L. Leaves, \( \varepsilon_w^* \), \( \varepsilon_{fL}^* \) and \( \varepsilon_{dL}^* \) 4-97
4.2.5 Power Output of Heating Source, 
\[ PO = PA_w = (PA/\text{Vol})_w \] by Water Heating Process 4-112
4.2.6 Electric Field Strength Inside and Outside of Water, \( E_{m(w)} \) and \( E_{o(w)} \) 4-125
4.2.7 Absorption Power of Fresh Leaves Mixture, \( (PA/\text{Vol})_{m_{fL}} \) of *Mesua ferrea* L. Leaves 4-131

4.3 Result II - *Mesua ferrea* L Leaves Essential Oils Extraction 4-151
4.3.1 *Mesua ferrea* L Leaves Essential Oils Preparation 4-151
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Comparison between conventional CET and recent MET methods for the isolation of EO from plants</td>
</tr>
<tr>
<td>2.1</td>
<td>Series of input data</td>
</tr>
<tr>
<td>4.1(a)</td>
<td>Dielectric properties (Exp&amp;Th) of water, $\varepsilon_{\omega}^<em>-\text{Exp}$, $\varepsilon_{\omega}^</em>-\text{Th}$ at 2.42 GHz and at 26 to 100°C</td>
</tr>
<tr>
<td>4.1(b)</td>
<td>Dielectric properties (Exp) of fresh, ($\varepsilon_{\omega}^<em><em>{\text{f}}$-Exp26°C) and dry, ($\varepsilon</em>{\omega}^</em>_{\text{d}}$-Exp26 to 100°C) <em>Mesua ferrea</em> L. leaves at 2.42 GHz and at 26 to 100°C</td>
</tr>
<tr>
<td>4.1(c)</td>
<td>Dielectric loss factor (Exp) of water, $\varepsilon_{\omega}^*_{\text{d}}$-Exp at 2.42 GHz and at 26 to 100°C due to dipole orientation</td>
</tr>
<tr>
<td>4.1(d)</td>
<td>Dielectric loss factor (Exp) of fresh, ($\varepsilon_{\omega}^<em><em>{\text{f}}$-Exp26°C) and dry, ($\varepsilon</em>{\omega}^</em>_{\text{d}}$-Exp26 to 100°C) <em>Mesua ferrea</em> L. leaves at 2.42 GHz and at 26 to 100°C due to ionic conductivity and dipole orientation</td>
</tr>
<tr>
<td>4.1(e)</td>
<td>Dielectric properties (Exp) of fresh, ($\varepsilon_{\omega}^<em><em>{\text{f}}$-Exp26°C) and dry, ($\varepsilon</em>{\omega}^</em>_{\text{d}}$-Exp 26 to 100°C) <em>Mesua ferrea</em> L. leaves at 2.45 GHz and at 26 to 100°C from various average evaporated moisture</td>
</tr>
<tr>
<td>4.2(a)</td>
<td>Time consumption, $\Delta t$ (min) during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C</td>
</tr>
<tr>
<td>4.2(b)</td>
<td>Absorption power of water, $(PA/\text{Vol})_w$ (W/m³) during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C</td>
</tr>
<tr>
<td>4.2(c)</td>
<td>Power output of heating source, $PO$ (W) or $PA_w$ (W) during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C</td>
</tr>
<tr>
<td>4.2(d)</td>
<td>Power output consumption of heating source, $POC$ (W) during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C</td>
</tr>
</tbody>
</table>
4.3 Electric field strength inside, $E_{in(w)}$ (V/m) and outside, $E_{o(w)}$ (V/m) of water during water heating process using MELs for eight volumes of water to obtain the specific temperature at 90°C at 2.42 GHz

4.4(a) Dielectric properties of fresh leaves mixture, $\varepsilon_{mfL}^*$ (Meas) at specific temperature of 26°C and at 2.42 GHz, and dielectric properties of fresh leaves mixture, $\varepsilon_{mfL}^*$ (Cal) from dielectric properties of dry leaves, $\varepsilon_{dl}^*$ (Meas) measured at 26 to 100°C and at 2.42 GHz

4.4(b) Dielectric properties of fresh leaves mixture, $\varepsilon_{mfLDD}^*$ (Cal) during DD and $\varepsilon_{mfLWD}^*$ (Cal) during WD at 26 to 100°C and at 2.42 GHz

4.4(c) Electric field strength inside of fresh leaves mixture, $E_{in(mfLDD)}$ (Cal) during DD and $E_{in(mfLWD)}$ (Cal) during WD at 26 to 100°C at 2.42 GHz

4.4(d) Absorption power of fresh leaves mixture, $(PA/Vol)_{mfLDD}$ (Cal) during DD and $(PA/Vol)_{mfLWD}$ (Cal) during WD at 26 to 100°C at 2.42 GHz

4.5(a) Sample heating or extraction process profile of fresh leaves mixture during DD and WD using MELs of MET at 60 min:100°C:450W:2.45 GHz in terms of time, temperature and power output during HD and SD using HM of CET at 60 min:100°C:450 W to obtain the first droplet of EO

4.5(b) Profile of the EO extraction process of Mesua ferrea L leaves

4.6(a) Output power used daily, $OP$ (kW/kg) using MELs of MET during DD, WD and HM of CET during HD and SD

4.6(b) Energy used. Daily, $En$ (kW/h) using MELs of MET during DD, WD and HM of CET during HD and SD

4.6(c) Actual power used daily, $P$ (kW/h) using MELs of MET during DD, WD and HM of CET during HD and SD

4.6(d) Extraction cost daily, $EC$ (RM/day) using MELs of MET during DD, WD and HM of CET during HD and SD
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Electromagnetic spectrum and frequencies used in microwave processing (Sutton, 1993)</td>
<td>2-16</td>
</tr>
<tr>
<td>2.2</td>
<td>(a) “Cooker Magnetron”; (b) Schematic diagram of a magnetron shown in cross-section</td>
<td>2-17</td>
</tr>
<tr>
<td>2.3</td>
<td>Propagation of a plane wave</td>
<td>2-19</td>
</tr>
<tr>
<td>2.4</td>
<td>Induced polarization of dielectric material</td>
<td>2-25</td>
</tr>
<tr>
<td>2.5</td>
<td>Dipole interaction (Evelyn Soon, 1996; Nyfors and Vainikainen, 1989)</td>
<td>2-29</td>
</tr>
<tr>
<td>2.6</td>
<td>Drying characteristic of liquid</td>
<td>2-32</td>
</tr>
<tr>
<td>2.7</td>
<td>A simplified flow diagram to estimate the absorption power of fresh leaves mixture, ((\text{PA/Vol})_{\text{in(\text{mL})}}(\text{W/m}^3)) during DD and WD in MET</td>
<td>2-52</td>
</tr>
<tr>
<td>2.8</td>
<td>A step by step procedure (1 to 8) to estimate the absorption power of fresh leaves mixture, ((\text{PA/Vol})_{\text{in(\text{mL})}}(\text{W/m}^3)) during DD and WD in MET</td>
<td>2-(53&amp;54)</td>
</tr>
<tr>
<td>3.1</td>
<td>The state of the art of the EO extraction process</td>
<td>3-56</td>
</tr>
<tr>
<td>3.2</td>
<td><em>Mesua ferrea</em> L. plants at Universiti Putra Malaysia, Serdang, Selangor, Malaysia</td>
<td>3-58</td>
</tr>
<tr>
<td>3.3</td>
<td>(a) The cut section of fresh <em>Mesua ferrea</em> L. leaves for moisture content determination, (b) The dimension of special design leaves holder, (c) An electronic balance (\pm 0.001) g, (d) A cross section of stacks of fresh leaves placed on its side in a 400 mL Pyrex beaker for moisture content determination, (e) An electronic drying oven (\pm 1^\circ)C and (f) A desiccator with blue silica gels where sample is cooled down to room temperature 26°C before weighing its dry weight</td>
<td>3-62</td>
</tr>
<tr>
<td>3.4</td>
<td>Setup for density of dry leaves determination</td>
<td>3-64</td>
</tr>
</tbody>
</table>
3.5 Open-ended coaxial line probe sensor coupled with automated network analyzer for dielectric properties measurement

3.6 [(a), (b), (c), (d)] Connection diagram and dielectric probe kit for HP85070B Systems, [(e), (f)] how to measure water, dry or fresh leaves and (g) An open-ended coaxial Line probe. A reflection method where the sensor is immersed inside the sample during measurement. The fields at the probe end “fringe” into the material, causing a reflection that can be related to the complex permittivity (Blackham et al., 1990)

3.7 Microwave Extraction Laboratory Systems

3.8 EasyWAVE 3.5 softaware interface; (1) Main screen of terminal controller, (2) Draw it, (3) EasyWAVE does it! And (4) Save it

3.9 Heating mantle

3.10 Rotary vacuum evaporator or rotavaps

3.11 Setup of distillation unit (Clevenger unit, Condensation unit and Chiller unit) for MET and CET

3.12 Setting parameter of EasyWAVE 3.5 for MET

3.13 Illustrated figure of (a) DD and (b) WD for extraction of EO using MELs of MET; (c) HD and (d) SD for extraction of EO using HM of CET

3.14 Experimental setup MELs of MET during DD and WD

3.15 Experimental setup HM of CET during HD and SD

3.16 (a) gas chromatograph (Shimadzu model GC-17A) and (b) gas chromatograph (Shimadzu GC-17A) coupled to a Shidmadzu GC-MS-QP5050A mass spectrometer

3.17 Setting parameter of EasyWAVE 3.5 for power output determination using MELs of MET

3.18 Setup of water heating process to determine the power output of heating source (a) using MELs of MET and (b) using HM of CET
4.1 Average evaporated moisture of fresh *Mesua ferrea* L. leaves from 26 to 100°C

4.2 Dry and wet density of *Mesua ferrea* L. leaves

4.3 Dielectric properties (a) Experimental, $\varepsilon_w'^*$-Exp (b) Theoretical, $\varepsilon_w'^*$-Th of water at 26 to 100°C and 0.13 to 20 GHz

4.4 Dielectric properties (a) Experimental, $\varepsilon_w'^*$-Exp (b) Theoretical, $\varepsilon_w'^*$-Th of water at 0.13 to 20 GHz and at 26 to 100°C

4.5 Dielectric properties (Exp) (a) Dielectric constant, $\varepsilon_w'^*$-Exp (b) Dielectric loss factor, $\varepsilon_w'^*$-Exp of water at 2.42 GHz and at 26 to 100°C

4.6 Dielectric properties (Exp) (a) Dielectric constant, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp (b) Dielectric loss factor, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp of fresh (26°C) and dry (26 to 100°C) *Mesua ferrea* L. leaves at 26 to 100°C and at 0.13 to 20 GHz

4.7 Dielectric properties (Exp) (a) Dielectric constant, $\varepsilon_w'^*$-Exp, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp (b) Dielectric loss factor, $\varepsilon_w'^*$-Exp, $\varepsilon_L'^*$-Exp of water (26°C) and fresh (26°C) and dry (26 to 100°C) *Mesua ferrea* L. leaves 26 to 100°C and at 0.13 to 20 GHz

4.8 Dielectric properties (Exp) (a) Dielectric constant, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp (b) Dielectric loss factor, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp of fresh (26°C) and dry (26 to 100°C) *Mesua ferrea* L. leaves at 2.42 GHz and at 26 to 100°C

4.9 Dielectric properties (Exp) (a) Dielectric constant, $\varepsilon_w'^*$-Exp, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp (b) Dielectric loss factor, $\varepsilon_w'^*$-Exp, $\varepsilon_L'^*$-Exp, $\varepsilon_L'^*$-Exp of water (26 to 100°C) and fresh (26°C) and dry (26 to 100°C) *Mesua ferrea* L. leaves at 2.42 GHz and at 26 to 100°C
Dielectric properties (Exp) (a) Dielectric constant, $\varepsilon'_\text{Exp}$ (Exp), $\varepsilon''_\text{Exp}$ (Exp) (b) Dielectric loss factor, $\varepsilon'_\text{Exp}$ (Exp), $\varepsilon''_\text{Exp}$ (Exp) of fresh (26°C) and dry (26 to 100°C) Mesua ferrea L. leaves at 2.45 GHz from various average evaporated moisture

Water heating process profile in terms of elapsed temperature of water and elapsed power output consumption of heating source using (a) MELs (b) HM for eight different volumes of water with respect to the elapsed time of process to obtain the specific temperature at 90°C

Time consumption, $\Delta t$ (min) profile during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C

Absorption power of water, $(PA/\text{Vol})_w$ (W/m$^3$) profile during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C

Power output of heating source, $PO$ (W) profile during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C

Power output consumption of heating source, $POC$ (W) profile during water heating process using MELs and HM for eight different volumes of water to obtain the specific temperature at 90°C

Electric field strength (a) inside, $E_{\text{in}}(w)$ (V/m) (b) outside, $E_{\text{o}}(w)$ (V/m) of water during water heating process using MELs for eight volumes of water to obtain the specific temperature at 90°C at 0.13 to 20 GHz

Electric field strength (a) inside, $E_{\text{in}}(w)$ (V/m) (b) outside, $E_{\text{o}}(w)$ (V/m) of water during water heating process using MELs for 200 mL volumes of water to obtain the specific temperature at 90°C at 0.13 to 20 GHz
4.18 Electric field strength (a) inside, $E_{in(w)}$ (V/m) (b) outside, $E_{o(w)}$ (V/m) of water during water heating process using MELs for 200 mL volumes of water to obtain the specific temperature at 90°C at 2.42 GHz

4.19(a)&(b) Dielectric properties of fresh leaves mixture, (a)&(b) $\varepsilon'_{mfl}$ (Meas) and $\varepsilon''_{mfl}$ (Meas) from fresh leaves at 26°C and $\varepsilon'_{mfl}$ (Cal) and $\varepsilon''_{mfl}$ (Cal) from dry leaves at 26 to 100°C and at 0.13 to 20 GHz

4.19(c)&(d) Dielectric properties of fresh leaves mixture, (c)&(d) $\varepsilon'_{mfl}$ (Meas) and $\varepsilon''_{mfl}$ (Meas) from fresh leaves at 26°C and $\varepsilon'_{mfl}$ (Cal) and $\varepsilon''_{mfl}$ (Cal) from dry leaves at 90°C and at 0.13 to 20 GHz

4.20 Dielectric properties of fresh leaves mixture, $\varepsilon'_{mfl}$ (Cal) and $\varepsilon''_{mfl}$ (Cal) from dry leaves at 26 to 100°C and at 2.42 GHz

4.21(a)&(b) Dielectric properties of fresh leaves mixture, (a) $\varepsilon'_{mfl,DD}$ (Cal) (b) $\varepsilon''_{mfl,DD}$ (Cal) during DD at 26 to 100°C and at 0.13 to 20 GHz

4.21(c)&(d) Dielectric properties of fresh leaves mixture, (c) $\varepsilon'_{mfl,WD}$ (Cal) (d) $\varepsilon''_{mfl,WD}$ (Cal) during WD at 26 to 100°C and at 0.13 to 20 GHz

4.22 (a) Electric field strength inside of fresh leaves mixture, $E_{in(mfl,DD)}$ (Cal) during DD and $E_{in(mfl,WD)}$ (Cal) during WD and (b) Absorption power of fresh leaves mixture, $(PA/Vol)_{mfl,DD}$ (Cal) during DD and $(PA/Vol)_{mfl,WD}$ (Cal) during WD at 26 to 100°C and at 0.13 to 20 GHz

4.23(a)&(b) Dielectric properties of fresh leaves mixture, (a) $\varepsilon'_{mfl,DD}$ (Cal) and $\varepsilon''_{mfl,DD}$ (Cal) during DD (b) $\varepsilon'_{mfl,WD}$ (Cal) and $\varepsilon''_{mfl,WD}$ (Cal) during WD, at 90°C and at 0.13 to 20 GHz

xxiii
4.23(c)&(d) (c) Electric field strength inside of fresh leaves mixture, $E_{in(mfLDD)}(Cal)$ during DD and $E_{in(mfLWD)}(Cal)$ during WD, and (d) Absorption power of fresh leaves mixture, $(PA/Vol)_{mfLDD}(Cal)$ during DD and $(PA/Vol)_{mfLWD}(Cal)$ during WD at 90°C and at 0.13 to 20 GHz

4.24(a)&(b) Dielectric properties of fresh leaves mixture, (a) $\varepsilon'_{mfLDD}(Cal)$ and $\varepsilon''_{mfLDD}(Cal)$ during DD (b) $\varepsilon'_{mfLWD}(Cal)$ and $\varepsilon''_{mfLWD}(Cal)$ during WD, at 26 to 100°C and at 2.42 GHz

4.24(c)&(d) (c) Electric field strength inside of fresh leaves mixture, $E_{in(mfLDD)}(Cal)$ during DD and $E_{in(mfLWD)}(Cal)$ during WD, and (d) Absorption power of fresh leaves mixture, $(PA/Vol)_{mfLDD}(Cal)$ during DD and $(PA/Vol)_{mfLWD}(Cal)$ during WD at 26 to 100°C and at 2.42 GHz

4.25 Dielectric properties of fresh leaves mixture, (a) $\varepsilon'_{mfLDD}(Cal)$ and $\varepsilon''_{mfLDD}(Cal)$ during DD (b) $\varepsilon'_{mfLWD}(Cal)$ and $\varepsilon''_{mfLWD}(Cal)$ during WD, (c) Electric field strength inside of fresh leaves mixture, $E_{in(mfLDD)}(Cal)$ during DD and $E_{in(mfLWD)}(Cal)$ during WD, and (d) Absorption power of fresh leaves mixture, $(PA/Vol)_{mfLDD}(Cal)$ during DD and $(PA/Vol)_{mfLWD}(Cal)$ during WD at 90°C and at 2.42 GHz

4.26 Sample heating or extraction process profile of fresh leaves mixture during DD and WD using MELs of MET at 60 min:100°C:450 W:2.45 GHz in terms of time, temperature and power output during HD and SD using HM of CET at 60 min:100°C:450 W to obtain the first droplet of EO

4.27(a)&(b) Results of (a) yield of EO, $EO(\%)$ for Mesua ferrea L. leaves, (b) Number of oxygenated and terpenes compounds, from various methods of extraction

4.27(c)&(d) Results of (c) Percentage oxygenated fraction of EO for Mesua ferrea L. leaves and (d) Percentage terpenes fraction of EO for Mesua ferrea L. leaves from various methods of extraction