# MODELLING THE DRYING KINETICS OF MICROWAVE DRYING OF COCONUT CHIPS

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Degree of Master of Science

Department of Chemical and Process Engineering

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Prof. M. Narayana, Professor, Department of Chemical and Process Engineering, University of Moratuwa.

## Abstract

Drying of coconut chips has been of interest for research due to the commercial value of coconut oil and desiccated coconut. More recently the industry has called for cost effective solutions for the drying unit operation of coconut chips used in the production of virgin coconut oil and desiccated coconut. This study was carried out to identify the parameters on which microwave assisted coconut drying kinetics were impacted and a mathematical model was developed to predict the microwave assisted drying behaviour of coconut chips. Drying time of coconut was found to depend on the microwave power and the mass loading when external parameters such as air velocity, air humidity, and shape factors of the coconut chips were kept constant. The drying behaviour was accurately predicted by several thin layer drying models and the Page model was selected due to its accuracy and simplicity. A new model was proposed to represent the parameters of the Page model as a function of microwave power. The proposed new model is given by, $MR = exp(\, a.exp\left(\frac{M}{P}\right).t^{(c.P+0.6)})$ where, a = -0.07 $min^{-1}$, M=37.29 $Js^{-1}$ and c = 0.0007 $sJ^{-1}$. Parameter *t* (time) needs to be substituted in minutes and *P* (power) in watts (W).

Moreover, the impact of mass loading was found to be effective only when the ratio of microwave power to mass loading (MPML) factor exceeded a value of about 3.7 $Wg^{-1}$. Under this condition, the diffusivity per unit of microwave power was found as $1.31\times10^{-11}$ $m^2s^{-1}W^{-1}$. A sharp decrease in the drying rate was observed when the moisture content approached approximately 30 % (w/w dry basis), indicative of changing from the removal of free moisture to removal of bound moisture. The quality of the desiccated coconut and virgin coconut oil were analysed based on the standards stipulated by the Sri Lanka Standards Institute and Coconut Development Authority. A process development road map was proposed based on the drying kinetics, rehydration ratio, cooling time and maximum temperature to meet the quality requirements.

Keywords: Model for drying, Desiccated coconut, Microwave drying kinetics, Drying rate, Drying technology

## Acknowledgement

"*It is the supreme art of the teacher to awaken joy in creative expression and knowledge"*

*– Albert Einstein*

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# TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF APPENDICES



## NOMENCLATURE

| Symbol/ Abbreviation | Description |
|---|---|
| $P_{v,s}$ | Water vapour pressure at the surface |
| $P_{v,a}$ | Water vapour pressure of the ambient |
| $P_v$ | Vapour pressure |
| T | Temperature |
| DR | Rate of drying ($min^{-1}$) |
| MR | Moisture ratio |

| | |
|---|---|
| m | Mass of wet solid (g) |
| A | Surface area of solid perpendicular to airflow direction ($m^2$) |
| X | Moisture content (w/w dry basis) |
| t | Time (minutes) |
| $V_p$ | Velocity of propagation |
| $\varepsilon'$ | Dielectric constant |
| C | Speed of light in air |
| $\varepsilon''$ | Dielectric loss factor |
| V | Volume |
| $S$ | Shrinkage |
| P | Microwave power (W) |
| $D_{eff}$ | Effective Diffusivity |
| MPML | Microwave power per mass loading ($Wg^{-1}$) |
| DC | Desiccated Coconut |
| VCO | Virgin  Coconut Oil |

# 1. INTRODUCTION

Microwave drying has become a popular drying technology with many industries yearning to adopt the technology due to its multifaceted benefits, which include [1]:

- Reduced total energy consumption for the drying unit operations [2]
- Reduced time for drying and higher efficiency [3] [4] [5]
- Improved quality and sensory properties in food industry [1] [4] [5]
- Higher yield during extraction of oils and nutrients [1] [3] [6]

Drying of coconut chips/ grated coconut is the most energy consuming, most costly and one of the most critical unit process in the production process of coconut oil and desiccated coconut. The oil derived from dried coconut is used in various applications such as the food industry, cosmetic industry and pharmaceuticals. Desiccated coconut has been an important export good in the past and Sri Lanka has refocused its attention to it due to the increase in global demand. This demands standardising the quality of the coconut oil and desiccated coconut required for various applications. The quality of the dried coconut has a direct impact on the quality of the final product, whether it is coconut oil or desiccated coconut. Therefore, it is important to study the drying operation in detail and identify critical parameters for higher quality while exploring the ability to adapt new technologies which can be cheaper and more efficient when scaling up the production process to cater to the global market.

There are various methods of drying and the optimum method of drying has to be reflective of lower energy consumption, lower time utilisation and superior quality of the final product. Moisture content of coconut needs to be reduced to around 6-7 % of moisture on dry basis to make good quality dry coconut to produce coconut oil and desiccated coconut. This study is aimed at evaluating the possible application of microwave assisted drying (MWAD) for coconut kernel based products in order to determine if MWAD is an optimum method of drying on an industrial scale.

Mathematical and numerical models for describing the transport of moisture inside copra during hot air drying have already been examined and the results were published by A.R.L. Mendis et al [7]. This study will focus on developing the drying process using microwave drying technology to produce coconut chips in an efficient and cost-effective manner while preserving the quality aspects. Further the study aims at defining the drying kinetics of the microwave assisted air drying process of sliced coconut meat in order to develop a mathematical model to predict the drying time and to identify the critical parameters that affect the drying process.

This study will also examine the other aspects such as the shrinkage behaviour to identify if the use of microwave to dry coconut has an impact on the physical properties of the final product. All the above aspects are required when aspiring to implement the drying technology on an industrial scale.

## 1.1 Objectives of the Study

- Study the drying characteristics of microwave assisted drying of coconut kernel
- Model the microwave assisted drying of coconut kernel considering the influence of microwave power and initial mass loading on the drying kinetics
- Identify the optimum power consumption for a given drying condition

# 2. LITERATURE REVIEW

This section consists of the literature review, carried out for the drying of coconut kernel using magnetrons that generate microwave as the dielectric heating source.

## 2.1 Drying Operation in Food Industry

Drying is one of the key unit operations in the food processing industry with applications ranging from pre-processing such as moisture removal to extract oils and final processing such as in the dried fruit industry. Drying unit operation involves removing water molecules (moisture) from the food. It is an energy intensive process that takes up a significant amount of production expenditure of dry-base products depending on the type of dryer, operating conditions, properties of food material, and efficiency of dryer.

It is widely documented that since primitive societies, humans used solar drying as a method of food preservation. Solar drying essentially reduces microorganism activity due to removal of moisture and increase of temperature without cooking the food. However, limitations such as quality deterioration of food, inability to control the rate of drying have been key reasons to develop controlled drying processes on an industrial scale. With the growth in population, food industry has evolved to cater to thousands of people at once. At present over 20 % of fruits and vegetables are dried to ensure a longer shelf life and to promote food security [8].

The evolving production landscape has pushed scientists and inventors to develop and optimise the drying processes in order to increase the production capacity and reduce the energy footprint without hindering the desired quality of the final dried product. When considering post-harvest bio-porous materials such as fruits and vegetables, many types of dryers using various drying technologies are applied. The most common dryer types for bio-porous material is the convective hot air dryer that has a drying chamber and trays to hold the food products. These are placed on movable trolleys that can be moved in and out of the drying chamber [9].

More recent studies have been focused on developing rapid forms of drying processes as opposed to the conventional slow drying processes such as hot air drying and solar drying [10].

### 2.1.1 Mechanism of Food Drying

Drying in simple terms mean the transport of moisture molecules from the liquid phase to the gaseous phase. Drying may be defined as the removal of moisture molecules by means of vaporization from a liquid solution, suspension, or other wet solids to form a dry solid. Thermal drying of a solid refers to the above phenomenon taking place by the supply of heat. To elaborate this, two processes can be identified during drying of a wet solid;

> Process 1: Energy is transferred as heat to the surface of the wet solid to remove the moisture present on the surface.
>
> Process 2: The internal moisture is transported to the surfaces of the solid so that it can be evaporated due to process 1.

Drying has a complex mechanism that always involves a simultaneous mass transfer of water from food to the ambient and a heat transfer causing the water to be transported. In most cases an airflow over the food passes and removes moisture from the surface of the food and out of the drying chamber [11].

The first process is governed by the gradient of water vapour pressure between the exchange surface $P_{v,s}$ and the adjacent atmosphere $P_{v,a}$ [12]:

$$\nabla P_v dr = P_{v,s} - P_{v,a} \qquad \textit{Equation 2.1}$$

From the above equation, it can be deduced that the first process is dependent on external conditions such as energy supplied to the water molecules, energy absorbed by the water molecules, properties of the convecting air stream such as relative humidity, temperature of the air stream, and air flow rate. Other factors such as solid surface exposed to the dry air, external and internal heat and mass transfer coefficients are also instrumental to the drying process of a solid [13] [14] [15] [16].

The drying behaviour of solids can be characterised by measuring the loss of moisture from the solid as a function of time. The drying rate can be expressed by;

$$Dimentionless\ drying\ rate\ DR = \frac{X_{t+dt} - X_t}{dt} \qquad \textit{Equation 2.2}$$

Where; $X$ is the moisture content (w/w dry basis) and $t$ represents the time. The equation for calculation of dry basis moisture content is given in equation 2.11 in section 2.3.2. $DR$ value is given in $min^{-1}$.

Many changes to the food takes place during drying which include, chemical reactions, changes to the texture, physical changes such as shrinkage, and phase changes. This may alter the properties of the intended final product and thus much attention has to be given to understand the mechanism by which drying takes place.

Water that is trapped within coconut meat is present as free water and bound water. Free water is the component of water molecules that form hydrogen bonds between other water molecules alone. Free water is lightly entrapped and therefore easily removed from the food during drying or extracted during mechanical extraction. Capillary forces hold water in channels which are mostly at a micro or nano-scale surrounded by components of the food material. Water that is held in this manner due to capillary forces is called bound moisture [17]. The water entrapped in this manner cannot escape easily due to the presence of a physical barrier. On the other hand, bound water molecules are water molecules that are electrostatically bound to other substances present in the food. Removing this water may be more complex than removing free water. A considerable amount of the water molecules in wet solids are not always in contact with only water molecules. They are surrounded by other food molecules such as long chains of carbohydrates, proteins and other minerals. When the polar water molecules are surrounded by these molecules which may also have poles, bonds are formed. These bonds often have different bonding energies than regular water-water bonds resulting in these water molecules displaying different physiochemical properties than bulk water especially in parameters such as melting point, boiling point, density, compressibility, heat of vaporization and electromagnetic absorption spectrum [17].

A clear definition of the intensity of the forces holding the water molecules within the coconut chip that is intended to be dried cannot be defined in a simple manner. The forces of the bonds may vary from very weak to very strong bonds which are dependent on multiple factors. This implies that when coconut chips are being dried, the water molecules that have the weakest bonds will evaporate quicker than the water molecules that are bonded by stronger bonds. Generally, when the water that is freely bonded evaporates, the rate of removal of moisture happens at a constant rate given the other external factors are kept constant. A “constant drying rate” can be observed since the bonding energy between water molecules are similar. Subsequently, the rate of drying drops as the moisture within the coconut kernel reduces and bonds that are more complex emerge between water molecules and other molecules within the coconut kernel. This phenomenon can be defined as the “Falling-rate drying” [18].

Therefore, it can be deduced that the constant rate period of drying is mostly governed by external factors such as air flow velocity, air flow rate, the relative humidity of the air, the temperature of the air, the surface area diffusing moisture to the air and so on [15] [16].

When the vapour pressure exerted by the food in the surrounding air reaches the vapour pressure of the given temperature and relative humidity level, the moisture content in the food remains unchanged due to the inability to remove further moisture. This is called the equilibrium moisture content of the coconut kernel. Thus, there will be a unique equilibrium moisture content value for coconut kernel at the given drying temperature and relative humidity value.

### 2.1.2 Expected Changes in the Food During Drying Unit Operation

Food stuff undergo many physical, chemical and biological changes during the drying unit operation. Firstly, a clear reduction in moisture is achieved in the drying operation which dries the coconut chips. Subsequent to the drying a volume reduction can be noted in the bio porous material. Porosity, is defined as the ratio of void spaces known as micro pores to the actual volume of the medium. The porosity changes with moisture content and other drying conditions as the apparent volume may change and pore volumes may also change [19]. Since moisture is removed during drying, a void is created in the porous food material. This leads to the porous structure collapsing due to the lack of support from the previously supported osmotic pressure extended by the entrapped moisture. This leads to a phenomenon that is referred to as shrinkage. The bulk porosity decreases if the pores are fused when the structure collapses as well as the volume reduction due to shrinkage [20]. However, studies have shown instances where the porosity increases as more void spaces are created while moisture is removed [19].

One other change most food material undergo during drying is browning. The coconut meat turns to a yellowish-brown colour with time when exposed to the environment. This is a process that occurs due to enzymatic activity [21]. Enzymatic browning can be observed in many food types including fruits and vegetables. However, during the drying process this enzymatic action is accelerated. Asanka J. et al notes the changes listed in Table 2.1, in their study carried out regarding quality parameters of dried kernel vs. dried pulverized kernel during storage [22].

*Table 2.1 Color change of dried pulverized kernel and dried kernel during storage [22]*

| Time (Week) | Dried Pulverized kernel | Dried kernel |
|---|---|---|
| 0 | Cream White | Cream White |
| 1 | Cream White | Cream White |
| 2 | Cream White | Cream White |
| 3 | Yellowish White | Cream White |
| 4 | Yellowish White | Cream White |
| 5 | Off Cream White | Low Cream White |
| 6 | Off Cream White | Low Cream White |

Though the definitions of the various colours are not provided in the study it is clear that when there is pulverization involved prior to the drying taking place, the browning rate is higher during storage for prolonged periods of time. Moreover, browning due to localized burning may take place during microwave drying of food stuff [2].

It is observed that in coconut meat drying, the microbial activity in the coconut meat is reduced during and after the drying stages leading to a longer storage/shelf life. The predominant reason for this is lower microbial activity due to the removal of moisture and increased temperature during the drying process [22].

## 2.2 Desiccated Coconut and Coconut Oil

Many derivatives of coconut oil and desiccated coconut are produced from dried coconut kernels and pulverized coconut chips of various sizes. Ideally, the coconut kernel should be dried till the moisture content reaches the equilibrium moisture content of coconut meat to store them safely. Typically, the equilibrium moisture content for coconut meat is around 6 % to 7 % wet basis in tropical countries.

### 2.2.1 Coconut Oil Production Process

There are two main oil extraction processes that are used in industrial scale operations in Sri Lanka. Coconut oil can be extracted after drying the coconut kernel or before drying the coconut kernel [23]. Suppose the oil is extracted before the kernels are rid of moisture, the oil extracted has to be refined to remove moisture to prevent the oil from becoming rancid and unsuitable for consumption [24]. The dry process is the most popular method in Sri Lanka and at present there are more than 250 oil mills and 60 desiccated coconut (DC) mills registered with Coconut Development Authority (CDA) with an annual export value of over Rs. 18 Billion [25].

Coconut oil can vary in physical properties and chemical properties according to the manufacturing process. The two main variants that are exported can be identified as RBD – refined, bleached and deodorised and virgin coconut oil (VCO). VCO has a clear texture and has a higher market value than RBD.

The first step in the production of DC and VCO is to pulverize the coconut kernels to suitable particle sizes using pin cutters before being loaded into dryers [22].

### 2.2.2 Quality Standards and Testing

There are several quality parameters to be considered in dried coconut kernels and final products, which are derived in the form of DC and VCO. The quality parameters are more stringent when the product is virgin coconut oil as compared to RBD coconut oil. The visual quality parameter includes the whiteness of the dried coconut kernel or pulverised coconut. Local burns may occur during drying and should be avoided. Lovibond tintometer [26] can be to measure the colour of oil extracted from dried coconut kernel. The oil content of the pulverised dried coconut can be determined using soxhlet extraction [27].

## 2.3 Microwave (MW) Assisted Convective Air Drying

Microwave heating has been in existence since the time of World War II. However, the application of microwave heating in drying unit operation has been slow to catch on in the industry. The two main reasons for this being, firstly, most engineers are not familiar with the microwave heating mechanism, and secondly, since many industrialist are satisfied with existing processes, some tend to reject radical innovation

[28]. Microwave assisted air drying (MWAD) has gained wide acceptance in the food industry since the inception of the technology due to the benefits it provides. Several studies on microwave drying applications have been reported for products such as bibola seeds [1], different forms of lignite [29] [30], apple pomace [31], rainbow trout [32] etc. Zhang Min et al in their article for Journal of Trends in Food Science & Technology, titled "Trends in microwave related drying of fruits and vegetables" notes the following extract. "Vega-Mercado, Gongora-Nieto, and Barbosa-Canovas (2001) considered the use of MW as the fourth generation drying technology" [33].

The mechanism of MWAD can be broken down into three process steps for most food materials with high moisture contents.

Process 1: Heating up phase, where the MW energy is converted into thermal energy by means of dielectric heating. This increases the surface moisture vapour pressure until it equals the vapour pressure of water in the convecting air stream.

Process 2: Rapid drying rate, in which the thermal energy generated during dielectric heating, vaporizes the moisture. However, the rate of moisture vaporization depends upon the pore structure and capillary flow of vapour within the porous food material.

Process 3: Reduced rate of drying, during which the energy needed to vaporize the moisture within the food material is less than the thermal energy generated due to the dielectric heating. [33]

This last stage may increase the local temperature within the food in excess of the boiling point of water and result in localized cooking and burning of food tissue. MW drying has some major disadvantages such as uneven heat distribution during drying, possible quality deviations from the expected final product, and in some cases the MW is unable to penetrate the product [4]. One other drawback of MW heating is the inherent non-uniformity of electromagnetic fields within the MW chamber. However, this problem can be overcome by using wave guides and continuously changing the position of the food to be dried within the drying chamber by means of a conveyor belt or rotating tray. One more deficiency is the rapid mass transport due to the rapid heating from MW power may result in a deterioration of quality or cause an unexpected deviation in the food texture. This phenomenon is known as 'puffing' due to the vapour pressure build up within the pores of the food material [34].

The advantages of MW drying in general can be identified as: the rapid drying resulting in lower time consumption, lower energy consumption, that leads to lower production costs compared to conventional methods of drying [35]. This is mainly attributed to the dielectric heating principle where heat is generated in the water molecules within the coconut kernel eliminating the need for heat conduction through the coconut kernel, which is mostly a heat insulator.

Drying with only hot airflow takes approximately 21 hours to reach the desired final moisture content and has low energy efficiency, especially during the falling rate periods [7]. The biggest reason for the long duration of drying is due to the rate of removal of moisture from the drying surface being greater than the moisture transported from within the solid to the drying surface. This results in a phenomenon known as shrinkage and case hardening, which subsequently result in even lower rates of heat and mass transfer. Moreover, coconut chips cannot be exposed to high drying temperatures as this may lead to the deterioration of quality aspects, such as colour of the dried coconut chips, alterations to nutrients, and sensory properties [36]. However, engineers and scientists have introduced many techniques to overcome the shortcomings presented by MW assisted air drying.

### 2.3.1 Mechanism of Heat Transfer during Microwave Drying

Drying of coconut kernel using Microwave dryers essentially differentiates the heating mechanism from hot air drying. It is important to know that MW and dielectrics are not forms of heat, rather forms of energy that transform into heat within the material that is subject to the waves [14]. The extent to which microwave is converted into heat within the coconut meat is dependent on the dielectric properties of coconut meat. Microwave is an electromagnetic wave. An electromagnetic wave travels at the speed of light in a vacuum, given by C in the equation 2.3. However, the velocity of the wave changes as it passes through different media.

$$V_p = \frac{C}{\sqrt{\varepsilon'}} \qquad \textit{Equation2.3}$$

The dielectric constant, $\varepsilon'$ can be identified in the above equation and it varies from material to material i.e. the coconut meat has a specific dielectric constant applicable to a given frequency of electromagnetic wave.

The microwave emitting from the magnetron travels within the air in the chamber. The electromagnetic wave emitted is subject to various phenomena that result in several impacts. First, the surface phenomena’s can be identified such as whether the Microwave is reflected, refracted, transmitted and repolarised due to the metal chamber, the turning tray, air inlet and outlet and of course the coconut chips [37].

The electromagnetic wave passing through the coconut meat converts the electromagnetic energy into heat in many ways. The most dominant energy conversion mechanism depends on the nature of material subjected to an electromagnetic field. These materials can be broadly categorised into four main categories. Conductors, insulators, dielectrics, and magnetic compounds.

In the case of wet coconut, the material can be categorised as a lossy dielectric material [14]. During the wave propagation within the coconut kernel many of the following phenomena may take place resulting in heat generated within the material.

- Dipolar rotation of polar molecules such as water molecules within the coconut. Dipolar rotation may also take place in induced dipoles due to the stresses generated by the electromagnetic field. The electric field of the microwave builds up and decays within the coconut several million times every second depending on the wave frequency of the Microwave. In the case of the study carried out the frequency was $2.45 \times 10^9$ Hz. During the build-up phase dipolar molecules rotate in a particular direction depending on the polarity. During the decay of the electromagnetic wave the polar molecules relax and go back to the initial state. This creates a rotation. This rotation converts the electrical field energy into stored potential energy, which is later converted into thermal and kinetic energy.
- Ionic polarization refers to the phenomena that takes place when the free ions within the moisture trapped inside the coconut meat are accelerated due to the electric field. This results in a random movement of ions at high speeds due to ions having a positive or negative charge. This results in random collisions in which the stored kinetic energy converts into thermal energy. This in turn means that a material with high ion content will have more collisions and thus the heat generated should be more and the temperature rise should be representative of that phenomenon. The water within the coconut is an electrolyte and has a content similar to human plasma [38].

Debye, in 1929 after an extensive study refined the complex dielectric constant which is used to describe the behaviour of electromagnetic waves interacting with material. The complex dielectric constant is given by the following equation;

$$\varepsilon = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + j\omega\tau} - j\frac{\sigma}{\omega\varepsilon_0} \qquad \textit{Equation 2.4}$$

$\varepsilon_{\infty}$ is the dielectric constant of the material at very high frequency and $\varepsilon_s$ is the dielectric constant at very low frequencies. $\omega$ is the angular frequency of the wave in rads$^{-1}$. $\tau$ is the relaxation time of the dipoles in (s). $\sigma$ is the conductivity of the material (Siemens m$^{-1}$). $\varepsilon_0$ is the dielectric permittivity of free space. This value is approximately $8.8542 \times 10^{-12}$.

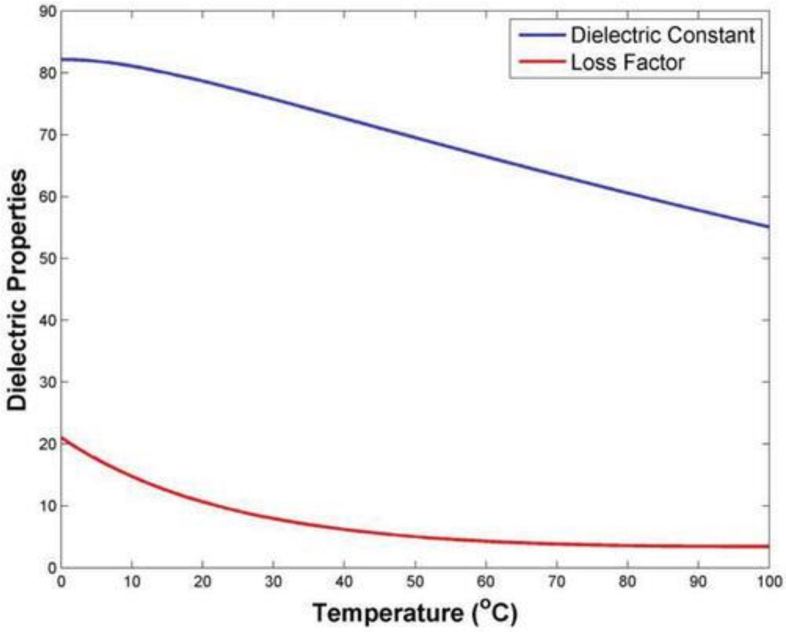
By separating the real part and the imaginary part of the complex dielectric constant and substituting a single parameter for the real part and imaginary part of the above equation, equation 2.4 can be written as;

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad \textit{Equation 2.5}$$

$\varepsilon'$ is referred to as the di electric constant that affects the impedance in the space taken up by the coconut meat (or any material that is in the path of the electromagnetic wave). Electromagnetic waves entering the space of the coconut is partially reflected at the interfacial boundary due the impedance. The wavelength of the electromagnetic field may change compared to the wavelength in air due to the impedance [39]. The di electric constant is a relative value due to the fact that an absolute impedance cannot be defined. In simple terms the di electric constant is a measure of how much of electric energy can be absorbed by the material.

The imaginary part of the complex dielectric constant, $\varepsilon''$ is known as the loss factor [40]. This represents the resistive nature of the material to conduct electricity. Therefore, this is a measure of how much of the absorbed electromagnetic energy is converted into heat. Since this value represents the loss of electricity within the material it is also referred to as the loss factor. However, it has to be noted that Debye's equation assumes that the material is homogenous throughout the space it occupies and hence assumes a uniform loss factor for a specific material.

The relaxation time $\tau$ is dependent on the temperature within the coconut for a given frequency. The relaxation time usually decreases with the increase of temperature within the coconut slices. Therefore, this results in the reduction of the loss factor as the temperature within the coconut increases. Further σ, conductivity within the coconut, changes with the removal of moisture from the coconut slices. This too affects the dielectric constant and the loss factor as the drying progresses.




Source: Energy transfer from electromagnetic waves to materials [37]

*Figure 2.1 Dielectric constant and loss factor variation with temperature of distilled water at 2.45 GHz.*

Figure 2.1 shows the variation of the dielectric properties with temperature of distilled water. Though this is not how it will vary within the coconut meat, this can indicate how these properties vary with temperature specifically at a fixed microwave frequency.

Sun et al. in their publication on composition-based prediction of dielectric properties of foods, investigated the influence of temperature and moisture content on the dielectric properties including the dielectric constant and loss factor. Since the proximate analysis of coconut has been evaluated in previous studies, to determine, moisture content, salt content, and ash content of coconuts collected in several parts of the world [41] [42] [43] [44], these values can be applied to the comprehensive models produced by Sun et al given in Equations 2.6 and 2.7. The temperature used in Kelvin within the range of temperatures from 278 K to 368 K, and wet ash content percentage and dry basis moisture content percentage has been considered.

$$\varepsilon'_{food} = m_{water}(41.0707 - 0.0018485.T) + m_{ash}(4.7947) + 8.5452$$ *Equation 2.6*

$$\varepsilon''_{food} = m_{water}(3.4472 - 0.001868.T + 0.000025T^2) + m_{ash}(-57.093 + 0.23109.T) + 3.5985$$ *Equation 2.7*

In a more recent study, titled dielectric properties of vegetables and fruits as a function of temperature, ash and moisture content, Sipahioglu et al. notes a different formula despite the methodology being similar [45]

$$\varepsilon'_{food} = 38.57 + 0.1255.T + m_{water}(0.4546 - 0.0037.T) - m_{ash}(14.54 - 0.07327.T)$$ *Equation 2.8*

$$\varepsilon''_{food} = 17.72 - 0.4519.T + 0.001382.T^2 + m_{water}(0.002206.T - 0.07448) + m_{ash}(22.93 + 0.1505.T) - 13.44\, m_{ash}^2$$

*Equation 2.9*

T = temperature value as applicable considering the temperature in ºC, $m_{water}$ = dry basis moisture (%), $m_{ash}$ = wet basis ash (%) is applied in the above equation.

### 2.3.2 Mathematical Modelling for Microwave Assisted Air Drying of Coconut Meat

A general method of building a model for microwave drying can be developed as per the following flow of data and information.

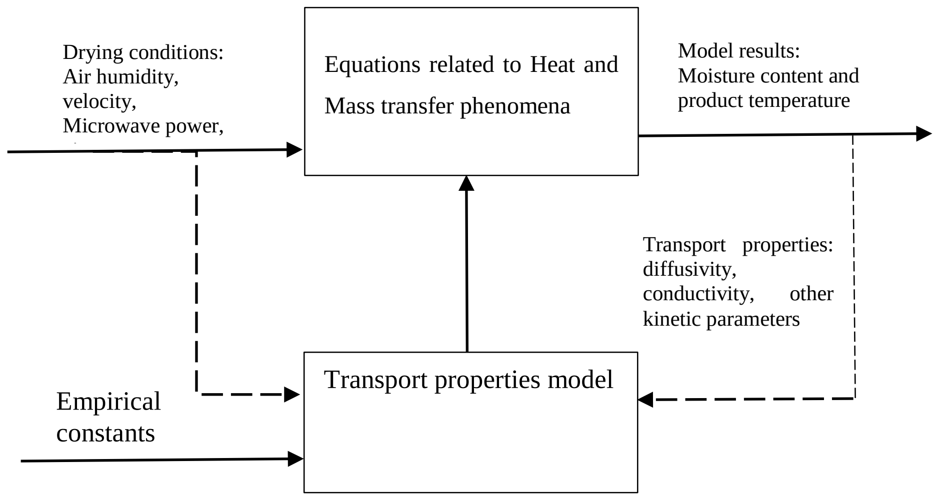



*Figure 2.2 Model information flow diagram*

Coconut kernel can be identified as a lossy dielectric material since moist coconut absorbs microwave energy and converts it to heat [14]. This is due to the water molecules, proteins and ionic compounds contained within the chipped coconut.

Factors to be considered to determine the heat and mass transfer properties of coconut dried in microwave dryer can be identified as follows. There are several aspects to consider including Microwave power absorption by the coconut, the conversion of the absorbed microwave into heat within the coconut at a given time, moisture level and microwave power intensity, the dispersion of the generated heat, the variation in power absorption at different levels of moisture content, and the effects of the microwave drying chamber and the form of the coconut placed within the chamber. Additionally, external factors such as the air flow rate, air humidity, air temperature at the inlet and outlet have a bearing on the heat and mass transfer behaviour of the coconut being dried. Therefore, model development becomes complex.

However, there are several empirical drying models available for drying that consider most of the internal and external factors as a bulk parameter. These models predict the moisture content as a function of time with constant representing factors such as, convecting air properties, drying temperature, mass loading etc. Therefore, one can use these models at fixed external factors during experimentation and vary only the mass loading assuming constant density and initial moisture content of the coconut, and the supplied microwave power. The data obtained by Microwave assisted coconut drying (MWAD) can be used to determine the best fitting model using curve fitting techniques. For example, Michael Bantle et al. identified the best fit as the modified weibull model in their study of MWAD of cupfish [2], and Zhwngfu Wang et al., found the modified Page model for drying of pre-treated apple pomace in microwave assisted dryer [46].

These models can be evaluated for identifying the best fit by using statistical analysis of curve fitting for calculating the correlation coefficient ( $R^2$), root mean square error (RMSE) and reduced chi-square ($\varkappa^2$) [47] [48] [6].

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N-z} \qquad RMSE = \left(\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}\right)^{\frac{1}{2}}$$

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)\left(MR_{pre,i} - \overline{MR}_{pre}\right)}{\sqrt{\sum_{i=1}^{N}\left(MR_{exp,i} - \overline{MR}_{exp}\right)^2 \sum\left(MR_{pre,i} - \overline{MR}_{pre}\right)^2}}$$

Some of the  commonly used drying models to evaluate the drying behavior of hot air drying (convection drying) and microwave assisted air drying are listed in Table 2.2 [47] [6] [2] [5].

*Table 2.2 Mathematical models given by various authors for drying curves [46]*

| No | Model Name | Model Equation |
|---|---|---|
| 1 | Newton | $MR = e^{-kt}$ |
| 2 | Page | $MR = e^{-kt^n}$ |
| 3 | Modified Page | $MR = e^{(-kt)^n}$ |
| 4 | Henderson and Pabis | $MR = a.e^{-kt}$ |
| 5 | Logarithmic | $MR = a.e^{-kt} + c$ |
| 6 | Two-term model | $MR = a.e^{-kt} + b.e^{-k_0 t}$ |
| 7 | Approximation of diffusion | $MR = a.e^{-kt} + (1-a).e^{-kbt}$ |
| 8 | Wang and Singh | $MR = 1 + at + bt^2$ |
| 9 | Midilli et al. | $MR = a.e^{-kt^n} + bt$ |

Where *a, b, c, k, n* are constants in models, *MR* and *t* are the moisture ratio and time respectively.

$$MR = \frac{X - X_{eq}}{X_0 - X_{eq}} \qquad \textit{Equation 2.10}$$

*X* is the moisture content and the subscripts *0* denotes initial condition, *eq* denotes equilibrium condition.

$$X = \frac{m_{water}}{m_{dry\ solid}} \qquad \textit{Equation 2.11}$$

The dry basis moisture content can be defined as the ratio of water to dry matter in the composite substance as given in Equation 2.11 where *m* denotes mass.

Subsequent to identification of the best fitting model for Moisture ratio and time data and validation based on a new data set, the model constants can be parametrically defined on external conditions that are varied. However, this analysis can be simplified by varying only one independent parameter at a time. In the case of this research, the mass loading (Initial mass of coconut placed in the drying chamber) and the microwave power were varied in 15 combinations as given Table 3.3 (in Chapter 3) i.e. Microwave power was supplied in 3 levels and mass loading had been changed in 5 different initial mass loadings for each microwave power.

### 2.3.3 Diffusivity and Activation Energy

Diffusivity generally refers to moisture diffusion taking place within a drying material. The parameter diffusivity refers to the passability of moisture from within the drying material to the air convecting the moisture away from the material. As the parameter diffusivity increases, the moisture removal increases and vice-versa. However when drying takes place, the diffusivity constantly varies throughout the process of drying due to various factors. The major factors include, the rate of heat and mass transfer, inter molecular forces, other forces acting on the transport of liquid within the microstructures of the coconut as well as the structural properties of the pores within the coconut meat. Therefore, a parameter called the effective diffusivity has been used widely to get an understanding of the water diffusion during an entire drying process.

Flick's second law of diffusion has been widely accepted as the governing equation of the diffusion driven drying process and many analytical solutions have been produced based on various assumptions to the original model developed by Flick.

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2}$$

Many past studies have developed several equations to calculate a value for the effective diffusivity. The falling rate period of drying was considered to determine the effective diffusivity ($D_{eff}$). According to Fick's law, the non-steady state diffusion can be expressed by [7] [49]:

$$lnMR = ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \qquad \textit{Equation 2.12}$$

Where, $L$ refers to the half thickness of the drying material and $D_{eff}$ is effective diffusivity in $m^2s^{-1}$.

### 2.3.4 Drying Unit Operation of Pulverised Coconut Kernel

There are many drying technologies used for drying of fruits and vegetables. Many new technologies have been developed and presently microwave aided drying technologies are popular among researchers due to the benefits discussed in previous sections. It is important to study the drying kinetics of each technology on each material to determine the optimal operating conditions to ensure that the quality of the final product is preserved while high drying rates are achieved.

When drying conditions of air is kept constant the drying kinetics, i.e the drying constants and drying rates will be representative of the coconut properties and drying process used.

Different techniques are employed to dry coconut meat in order to produce coconut oil in Sri Lanka and all over the world. Some of these techniques are used in the production process of desiccated coconut too. The most primitive and cheapest form of drying the coconut kernels, commonly referred to as copra, is solar drying. This process lasts approximately 10 days. Moreover the maximum reduction in moisture content observed is above 10 % (w/w, dry basis) which may result in the final coconut oil being rancid [50]. Moreover there is a high risk of microbial and fungi contamination on the product due to the exposure to harsh environmental factors. Other factors such as requirement of large expanse of space is needed for this. Most popular method of drying the coconut kernels is hot air drying, but it has a significant drawback of uneconomical energy consumption and long drying time.

Studies have been carried out to determine the optimum operating conditions and drying kinetics of coconut kernel (and copra) for hot air drying. The optimum temperature of hot air drying has been determined to be 60 ºC during the falling rate period. Further a two-stage process is recommended for drying of coconut kernels when drying using hot air dryers [7].

Generally the hot air drying technique takes approximately 21 hours for drying coconut kernels to the desired moisture content of 7-8 % (w/w, dry basis) [7]. Moreover, relative humidity and air flow velocity have been identified as key factors contributing to the kinetics of hot air drying of coconut kernel in addition to the drying temperature [50].

By introducing a microwave heating method the drying time of the drying process can be drastically reduced due to the rate of heat transfer in dielectric heating [51]. Microwave drying is not applied for coconut meat drying in DC or VCO industries at present. This may be due to the lack of input from research in the past on this important drying technology for coconut kernels.

### 2.3.5 Fabrication of Microwave Assisted Convective Air Dryer

The fabrication of the experimental setup for validation and acquiring data sets was critical in carrying out the proposed research. Several aspects have to be considered in constructing the Microwave assisted air dryer suitable for drying coconut.

Firstly, the choice of microwave generator. Microwave penetration into food types reduces with the increase of frequency of the microwave length. A 2450 MHz magnetron was selected due to safety aspects despite waves with lower frequencies may have higher penetration depths resulting in better wave penetration properties [33].

When metal parts are used, it can result in electron build up within the metal parts and result in sparking [52]. Therefore, an electron discharging mechanism should be put in place to ensure safety. An earthing system can be built into the parts exposed directly to microwave which do not have adequate protective coatings.

A Mica based waveguide has to be used to ensure that microwave can be directed at the food for efficient heating [53]. Openings have to be made to ensure a uni-directional laminar flow of dry air so as to remove the moisture from the coconut drying surface. An air blower can be used with openings and exhaust mechanism to ensure airflows at a constant velocity.

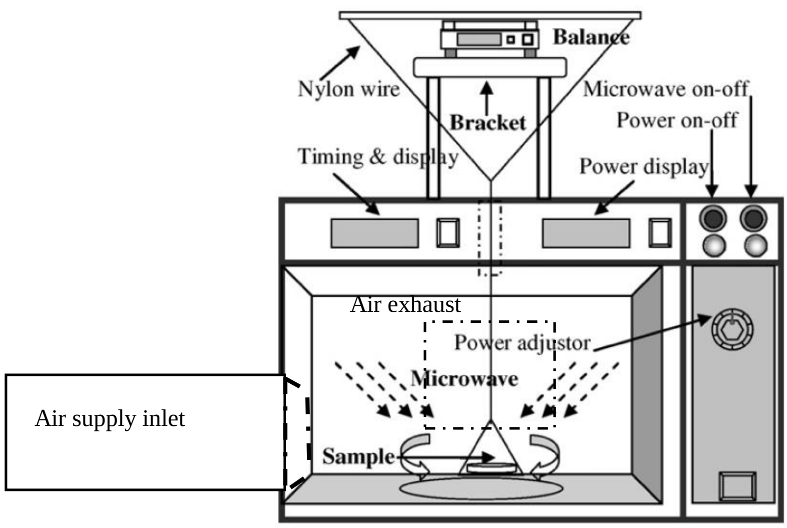



*Figure 2.3 Schematic of Microwave Assisted Convective Air Dryer suitable for laboratory scale coconut meat drying [46]*

Samples can be weighed continuously to obtain weight readings as shown in Figure 2.3. However these readings are subject to errors due to external forces acting on the chord and tray suspending the coconut chips in mid-air. Therefore a more accurate measure of the weight of the samples may be obtained by intermittently stopping the drying process at given intervals and weighing the samples and resuming the drying process. This method has been used by many researchers engaged in the study of microwave drying of food types [2] [51]. Figure 2.4 shows the set-up used for hot air drying of coconut.

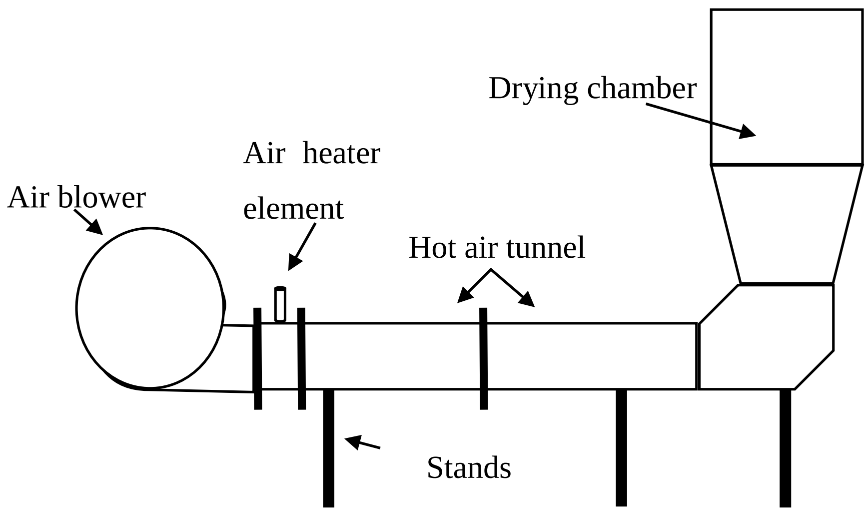



*Figure 2.4 Hot air coconut drier set-up*

# 3. MATERIALS AND METHODS

## 3.1 Sample Preparation

Well ripened, fresh coconut procured in bulk from the open market at Katubedda, Moratuwa (6.7881°N, 79.8913 °E) in Sri Lanka was stored at 27 ºC± 4 ºC in a dry area inside the lab with the shell intact. Coconut, when kept intact with the shell can be stored for approximately 15 days without much loss of moisture within the endosperm.

These coconuts were picked from the wet zone of Sri Lanka in the western province. The coconut was split into two halves and the coconut water was drained. The coconut solid endosperm was extracted with a fine layer of endocarp with a surgical Scalpel Blade No. 12D. The fine layer of endocarp was then shaved off leaving the white coconut meat (endosperm), which is used in coconut oil production. The coconut meat was then diced into approximately 1 cm × 1 cm × 1 cm cubes. The initial moisture content of the coconut was obtained from drying three 30 g samples in an oven at 105 ºC for 21 hours according to the Association of Official Agricultural Chemists (AOAC-1999) method for measuring moisture content during each of the experiments [54]. The average initial moisture content varied from 60 % to 110 % (dry basis), depending on the coconut.

The same procedure of sample preparation was followed for experiments designed to determine shrinkage and for measuring the temperature profile of the coconut pieces.

## 3.2 Experimental Strategy

Three types of experiments were carried out to understand different behavioural aspects of coconut in the microwave dryer.

*First type: Effect of microwave power and mass loading on drying time.*

A two factor, multi-level factorial design was used for the experiment. The effect of two independent variables Microwave Power $X_1$ (100 W, 180 W, 300 W) and Mass Loading rate $X_2$ (20 g, 40 g, 60 g, 80 g, 100 g) on three response variables, drying time, drying rate, and moisture content.

*Second type: Shrinkage behaviour in microwave drying*

The shrinkage of the solid coconut chips was studied with reference to the variation of the drying technology. The shrinkage data of MW assisted air drying was compared to the shrinkage data obtained by hot air drying of coconut pieces. The experiments were carried at fixed mass loadings of 50 g, and 100 g with a varying input power of 100 W, 180 W and 300 W respectively. The volume was measured using the Archimedes principle and noted against the instantaneous moisture content at given time intervals.

*Third type: Surface and internal temperature of the coconut during drying*

Experiments were carried out to measure the temperature of the external surface and internal volume of the coconut with the progression of the drying. This was done to determine the temperature profile within the coconut at various microwave powers and moisture contents.

The external surface temperature ($T_S$) of the coconut pieces were obtained using a Fluke 62 Max+ Infrared Thermometer with a reading accuracy of ±1 ºC. The surface temperatures of five selected coconut cubes were measured and recorded. The average reading was considered as the surface temperature. The temperature within the coconut cubes were obtained using a 40-gauge (0.04 $mm^2$) thermo couple. The thermocouple was inserted about 0.5 cm deep at 3 points of the 5 selected samples. The perforations were perpendicular to the long axis of the coconut cuboids at 3 different positions from the drying surface to the bottom surface. 3 individual readings of each coconut cuboid were taken after a 3 second settling time and the average temperature of the 15 readings were considered as the internal temperature at the given moisture ratio [55].

The same process was repeated at 10 moisture ratios at equal time intervals for the three microwave powers.

### 3.3 Fabrication Procedure of Microwave Assisted Dryer

A programmable domestic microwave oven (MW73AD-B, Sinhagiri Pvt Ltd, Sri Lanka) with a cooking chamber of 366 × 225 × 273 ($W \times H \times D$ mm$^3$) and the maximum power output of 800 W was used. The frequency of the microwaves generated by the magnetron of the dryer was 2450 MHz and it was used to perform all the drying experiments. The cooking chamber consists of a Triple Distribution System to ensure dispersion of Microwave (MW) within the cavity. The Microwave oven was modified by making openings on two walls of the cooking chamber and protective outer chamber to allow the air flow within the cooking chamber as shown in Figure 2.3. An air blower was used to circulate air with an average velocity of 1.0 ms$^{-1}$ in the drying chamber to ensure convective mass transfer [49] [3]. Considering the requirement of changeovers of air at room temperature (25 ºC) and relative humidity of 80 % within the 0.02 m$^3$ drying chamber (microwave cavity), a maximum air velocity of 0.37 ms$^{-1}$ is sufficient to remove moisture of up to 200 g of wet coconut meat when the supplied microwave power is 300 W (maximum drying rate for the experiment). Since the air velocity is almost 2.5 times higher than the maximum air changeover requirement for the removal of moisture from the coconut, the air flow velocity will not have in impact on the drying rate as it is not a limiting factor and is available in abundance.

Since many openings are made, there was a possibility of microwave radiation leaking to the immediate surroundings. Therefore, a further protective chamber was fabricated to ensure safety during experiments (Figure 3.1).

*Figure 3.1 Microwave assisted air dryer designed and fabricated for the experiments*

The following precautionary measures were undertaken to ensure that there were no safety concerns regarding leakage of microwave during the drying operation using the fabricated microwave dryer.

- Buffer of absorptive materials were places near openings despite it being sealed
- Outer protective chamber with well-sealed doors
- Use of Microwave leakage detecting to ensure there was no leakage detected during the drying process

### 3.4 Procedure to Determine Drying Kinetics of Microwave Assisted Drying

Coconut cubes were dried at different output powers (100, 180 and 300 W) for different sample loadings. Power beyond 300 W proved to exert a high rate of heat transfer to the water molecules within the pores of the cubed coconut kernel. When the rate of heat transfer was higher than the rate of moisture diffusion to the convective air stream, localised burning of the pulverised coconut cubes could be observed.

In each of the drying experiments, coconut cubes were placed randomly on the rotating tray within the cavity of the microwave dryer set up, resulting in a uniform distribution of microwave power. The coconut cubes were removed periodically for a very short time span, at five minutes intervals to record the weight.

A digital balance of 0.001g precision (KERN PCB 350-3, Germany) was used to measure the mass. Three different drying trials were conducted at each microwave power and each initial mass loading and the average values obtained from these trials were considered for the empirical model development. The Table 3.1 shows the sample loadings and powers that were used for the experiments.

*Table 3.1 Experiment number to determine drying kinetics of coconut kernel drying using MW assisted dryer*

| MW Power | | 100 W | | | | | | 180 W | | | | | | 300 W | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Loading | | **20 g** | **30 g** | **40 g** | **60 g** | **80 g** | **100 g** | **20 g** | **30 g** | **40 g** | **60 g** | **80 g** | **100 g** | **20 g** | **30 g** | **40 g** | **60 g** | **80 g** | **100 g** |
| Trial No. | **1** | 1 | 4 | 7 | 10 | 13 | 16 | 19 | 22 | 25 | 28 | 31 | 34 | 37 | 40 | 43 | 46 | 49 | 52 |
| | **2** | 2 | 5 | 8 | 11 | 14 | 17 | 20 | 23 | 26 | 29 | 32 | 35 | 38 | 41 | 44 | 47 | 50 | 53 |
| | **3** | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 | 33 | 36 | 39 | 42 | 45 | 48 | 51 | 54 |

## 3.5 Procedure to Determine Shrinkage during Microwave Assisted Drying

Experiments were carried out to determine the volume shrinkage of the coconut cubes during microwave drying. Two initial mass loadings, 50 g and 100 g, and the same three microwave powers, 100 W, 180 W and 300 W, were used in this experiment. Similarly, hot air drying was carried out at 60 ºC for the same two initial mass loads.

The drying procedure was as described in section 3.4, where the samples were randomly placed on the rotating tray and the mass was recorded in intervals of 5 mins. The volume of the total sample was determined by the Archimedes principle. The displaced toluene volume was determined using a displacement vessel (Figures 3.2 and 3.3) and measuring cylinder.

*Figure 3.2 Displacement Vessel*

The coconut cubes after weighing, were wrapped using cling film with a negligible volume and carefully descended into the displacement vessel filled with toluene. Liquid displacement method was used to measure the initial volume ($V_{initial}$) and final volume ($V_{final}$) of the wrapped coconut cubes [56]. The cubes were wrapped to reduce absorption of liquid into the cubes and to reduce any reactions that may occur if in contact with the coconut meat [57]. The excess toluene was dabbed off using tissues before placing the samples back in the dryer.

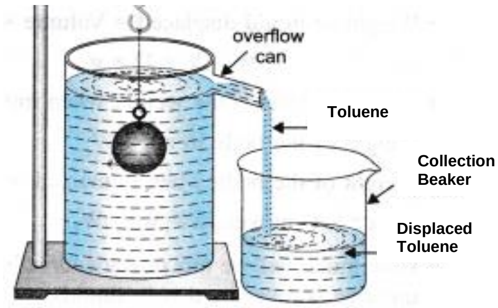



*Figure 3.3 Experimental setup to determine volume of pulverised coconut*

Solid volume is a property that can be conserved due to low compressibility. The total volume at a given time consists of the following components,

$$V_0 = \varphi_0 V_0 + V_{w,0} + V_S$$

$$\therefore V_S = (1 - \varphi_0)V_0 - \rho_w m_{w,0}$$

Similarly,

$$V_S = (1 - \varphi_t)V_t - \rho_w m_{w,t}$$

$$(1 - \varphi_0)V_0 - \rho_w m_{w,0} = (1 - \varphi_t)V_t - \rho_w m_{w,t} \quad \textit{Equation 3.1}$$

Where, $V$= volume, $\varphi$= fractional porosity, $\rho_w$= density of water, $m_{w,t}$= mass of water at time $t$ and $m_{w,0}$ mass of water at the beginning. Subscript *s* refers to solid, 0 refers to initial condition and subscript *t* refers to condition at any given time *t*.

Similar models have been proposed by Katekawa et al, and Madiouli et al in their work [58] [59]. However, the initial porosity of the material has to be known to use the above equations.

$$Shrinkage\ S = \frac{V_t}{V_0}$$

According to a study published in 2018 by Madiouli et al. regarding porosity and shrinkage curves of drying food material, an ideal shrinkage value can be calculated based on an equation proposed by the authors [19]. The ideal shrinkage refers to the shrinkage achieved if no change in porosity occurs during the entire drying process.

$$S_{ideal} = \frac{\rho_0}{1+X_0}\left(\frac{1}{\rho_s} + \frac{X}{\rho_L}\right) \qquad \text{Equation 3.2}$$

Where; $S_{ideal}$ is the ideal shrinkage value, $\rho_0$ initial bulk density in kg/m$^{-3}$, $X_0$ initial dry basis moisture content of the drying food, $\rho_s$ solid density, $X$ is the moisture content dry basis at the given moment, and $\rho_L$ the liquid density.

**3.6 Mathematical Modelling and Drying Kinetics**

Developing a mathematical model to predict the drying behaviour primarily means that the moisture removal with time can be predicted along with any other required information such as the drying rate. Some models can also be built to predict moisture distribution, temperature profiles and special properties of drying as given in studies published by authors such as Ismail et al. and Fu et al. for lignite and rainbow trout. Since we are more interested in the variation of moisture ratio with time and the effect of microwave power on the drying at any given time, the drying models given in Table 2.2 were tested and statistical curve fitting techniques were used to identify the best model.

This was done by curve fitting a substantial data set using MATLAB. Thereafter the model was validated using a fresh data set. Once the best suited thin layer drying model was identified, the constants were determined parametrically as a function of microwave power. This was done by assigning several types of functions of microwave power to the model constants. For example, if the Henderson Pabis model is selected, $MR = a.e^{-kt}$ the constants $a$ and $k$ can be assigned with functions considering a linear, exponential, logarithmic or Arrhenius relationship with microwave power ($P$). Since there are 2 variables and 4 possible types of functions that are considered for each variable, the number of possible equations are 16. By solving the above regression problem, a most suitable model including the moisture ratio ($MR$), the drying time ($t$), and the microwave power ($P$) can be developed. The final model can be validated against a new data set that was not used in constructing the drying model.

Based on the volume reduction data, a relationship between the moisture content and shrinkage during microwave drying can be developed for different microwave power levels which represent the rate of drying. This is important to determine the density and textural properties of the final dried coconut especially in applications such as producing coconut oil and desiccated coconut.

The models proposed by Sun et al. were used to determine the dielectric properties at various moisture levels and temperatures [60]. This data can be used to expand the above model to include dielectric properties.

### 3.7 Quality and characterization

When considering quality and characterisation of the dried coconut using the microwave assisted dryer, the application of the dried product has to be considered. There are different parameters to be considered in different countries for different applications of dried coconuts.

The essential quality parameters that may be affected by the drying process and consequently the production of coconut oil can be listed as follows.

1. Free fatty acid and acid value of the coconut oil: The AOCS Official Method Ca 5a-40 [2017] can be used to determine the free fatty acids in the coconut oil.
2. Colour of the coconut oil can be measured using a Lovibond colour comparator [tintometer]
3. Moisture content: The moisture content has to be measured using the standard oven method as specified in the ASTM standards for testing of virgin coconut oil. The oil sample is placed in the oven at 105 ºC for 24 hours to determine the moisture content.

Though various other parameters including the saponification value, iodine value, insoluble solid content and so on have to be determined prior to commercialisation, the drying technology has no direct impact on these parameters.

Similarly, desiccated coconut can be produced by drying in microwave assisted air dryer. The SLS 98 (2013 revision) provides clear quality parameters that need to be identified in desiccated coconut. However, as in the case of the production of coconut oil, the quality parameters directly affected by the drying process can be considered. Hence, the tested quality parameters are;

1. Moisture content: The moisture content can be measured using the standard oven method as specified in the SLS 98 standard. The desiccated coconut sample is placed in the oven at 105 ºC for 24 hours to determine the moisture content.
2. Colour of the desiccated coconut can be measured using the Lovibond colour comparator [tintometer].

Parameters such as the fat content, cut grading and nutritional composition are not affected by the drying process and therefore were not analysed under this study.

### 3.8 Drying efficiency and energy aspects

Microwave drying is regarded as a drying technique with high efficiency due to the energy transferring directly to the solvent (water) and not to the substrate (coconut meat) unlike the conventional hot air drying methods [14].The drying efficiency can be calculated by taking into account the specific energy consumption of the different modes of drying. The theoretical heat consumption can be analysed by calculating the heat required to remove an "X" mass of water from the coconut. This value can be compared with the actual energy consumed during microwave drying. Thereafter the same value can be compared with other modes of drying to determine the advantages in terms of energy consumption in order to carryout economic evaluations to determine the financial feasibility of industrial applications.

# 4. RESULTS AND DISCUSSION

## 4.1 Influence of Process Variables

There are many variables affecting the drying process in microwave assisted drying of coconut kernel. This section evaluates the influence and response of moisture content (represented using moisture ratio), time and the microwave power.

The effect of microwave power was studied at three microwave powers generated from the magnetron in the drying cavity. The increase in microwave power denotes a higher amplitude of the microwave. The rate of drying increases as higher amplitude of microwave will result in larger amount of energy delivered to the coconut. The time to attain the equilibrium moisture content of 6 % (w/w dry basis) from an initial moisture content of 85±5 %, for an initial mass load of 80 g was found to be 100 minutes, 195 minutes and 420 minutes for corresponding microwave output powers of 300 W, 180 W and 100 W respectively as shown in Figure 4.1. As expected, the time of drying was inversely proportional to the applied microwave power.

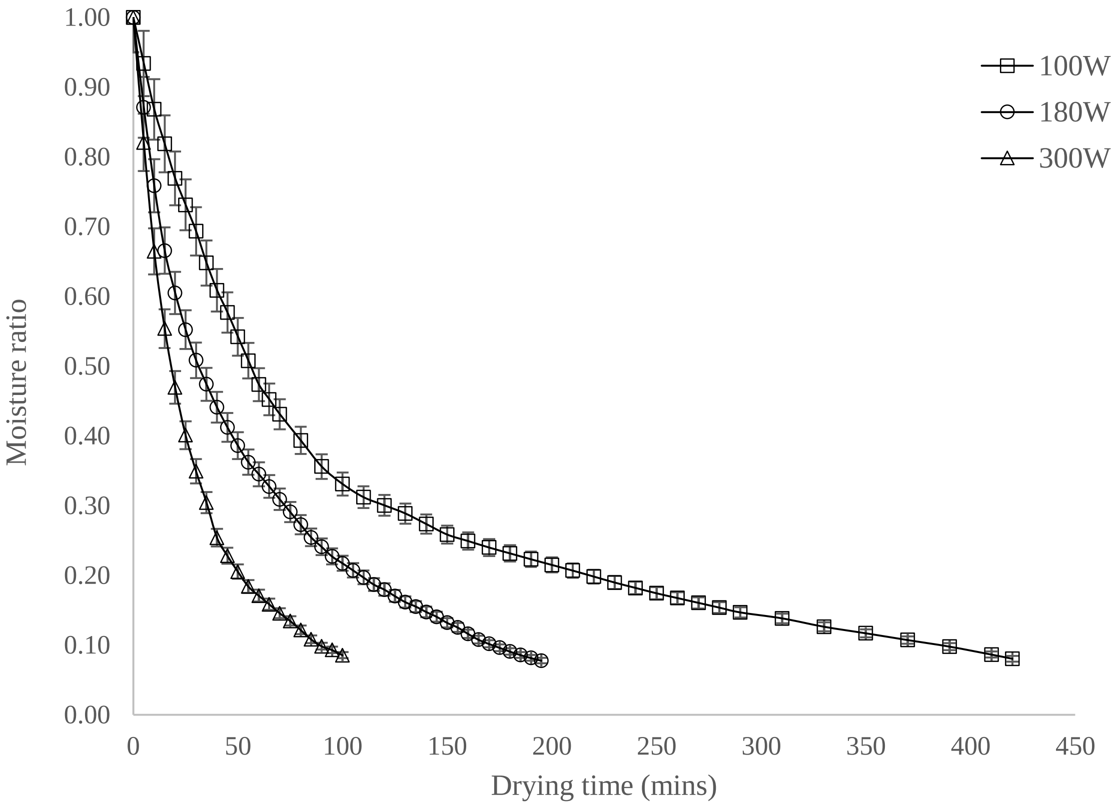



*Figure 4.1 Drying curves at initial sample loading of 80 g and different MW powers*

A reduction of  53 % of total  drying time was observed when the microwave power was increased from 100 W to 180 W and the total drying time further reduced by 43 % when the power was further increased from 180 W to 300 W. This effect was further examined by changing the intial mass load and the results are shown in Figure 4.2.

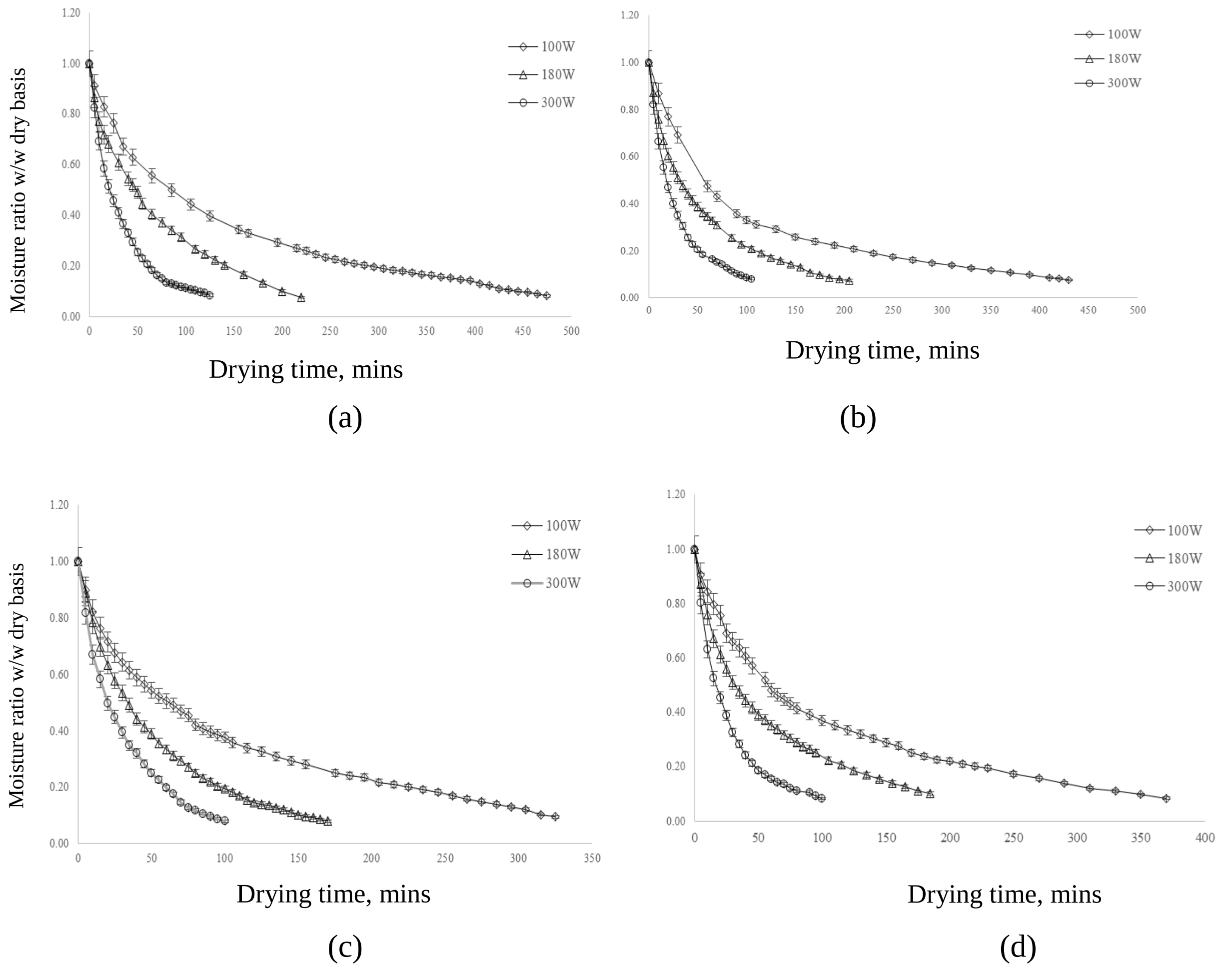



*Figure 4.2 Drying curves for pulverised coconut at various microwave powers and initial mass loading of (a) 100 g, (b) 80 g, (c) 60 g and (d) 40 g*

Figure 4.2 shows that the significance of the initial mass loading on the drying time has lower impact than the influence of microwave power on total drying time. The plot of total drying time at different mass loads given in Figure 4.3 summarizes the combination effect changing both the initial mass loading and the microwave power.

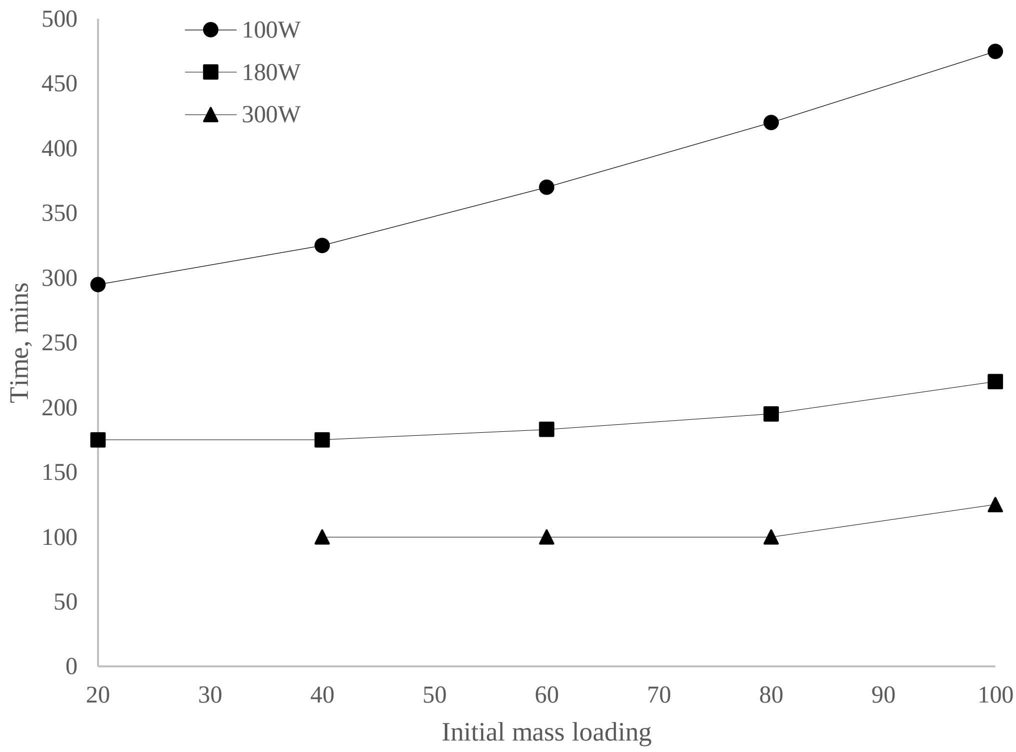



*Figure 4.3 Total drying time Vs. Initial mass loading at different microwave powers*

The total drying time remains constant for high microwave powers and at low mass loadings but starts to deviate with the increase of mass loading. At 300 W, the total drying time increased only beyond 80 g of initial mass loading. When the supplied microwave power was 180 W for initial mass loadings of 60 g and above resulted in a significant increase in drying time. On the other hand, an increasing trend of total drying time was evident for 100 W even at low initial mass loadings. This observation suggests that, the dependence of initial mass loading will come into effect at a minimum initial mass loading for a given microwave power. The dependence of initial mass loading can be ignored if the initial mass loading is below this critical value. This critical value may change from dryer to dryer and material to material at the same microwave power as the dryer dimensions and other operating parameters have an influence on drying behaviour during microwave drying [49].

Figure 4.3 shows that mass loading has been a significant factor when the microwave power is at 100 W. This is because the moisture diffusivity within the coconut samples are low at lower microwave power levels. This is a typical trend reported by many researchers ( [61], [62]), for drying of food material. Figures 4.4, 4.5 and 4.6 signify this behaviour for the three different microwave power settings.

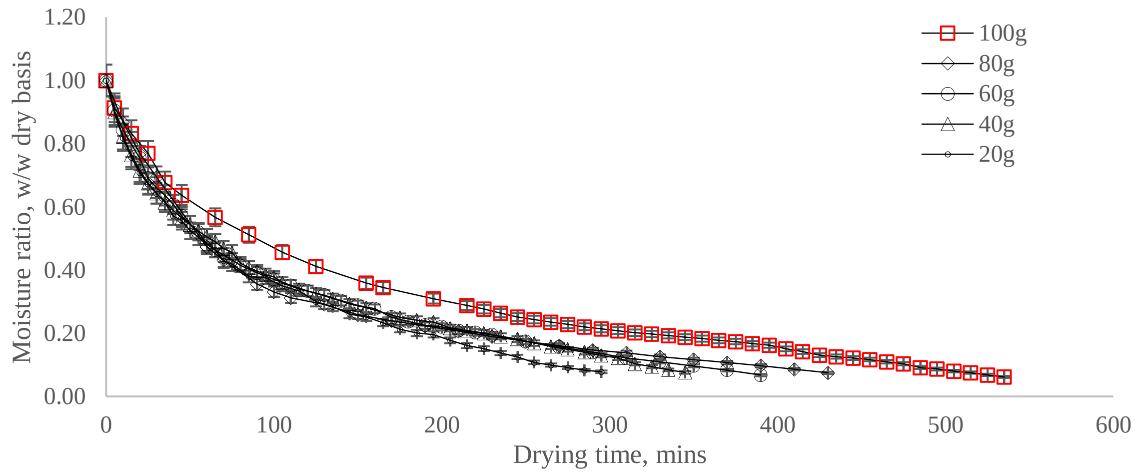



*Figure 4.4 Drying of sliced coconut meat at 100 W output microwave power and different mass loading*

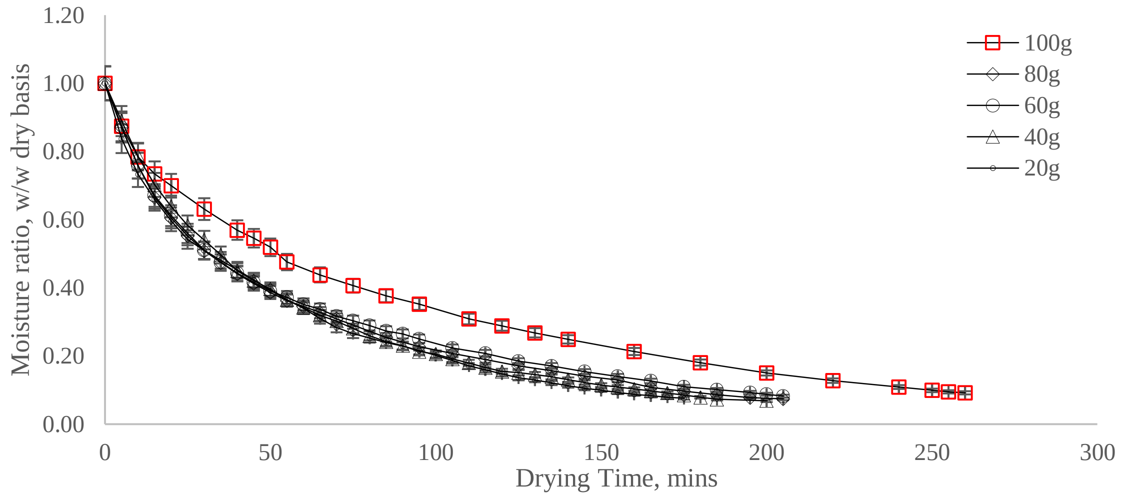



*Figure 4.5 Drying of sliced coconut meat at 180 W output microwave power and different mass loading*

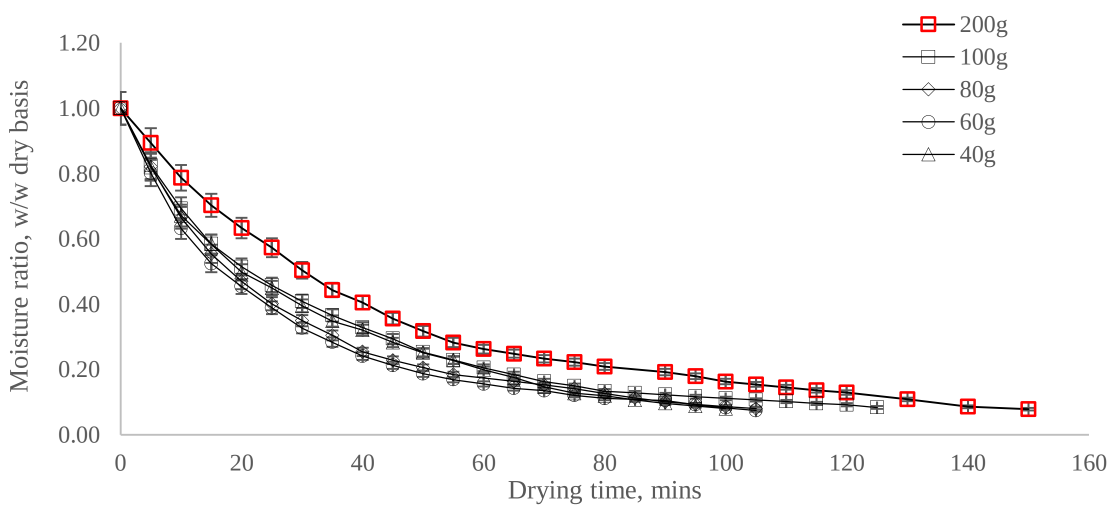



*Figure 4.6 Drying of sliced coconut meat at 300 W output microwave power and different mass loading*

Based on these results, a new term can be defined as the microwave power per initial mass load (MPML) of the drying material.

$$MPML = \frac{Microwave\ power}{Initial\ mass\ loading}$$

For 300 W, the critical mass loading is around 80 g and the MPML value is approximately 3.7 $Wg^{-1}$. For 180 W, the critical mass loading is in the range of 40 – 60g. If the MPML ≅ 3.7 $Wg^{-1}$ is taken as the reference, the critical mass loading for 180 W is around 48 g and the Figure 4.3 verifies it. With a similar calculation, the critical mass loading for 100 W can be computed and the value is around 27 g. However, the details in Figure 4.3 is insufficient for verification. This study was carried out on one material in one custom built dryer with 3 microwave powers available with the in-built magnetron. Therefore, further studies are required to identify the possibility of defining MPML for a specific drying unit and a drying material and to generalize this phenomenon.

In conclusion, supplied microwave power has a great influence on the total drying time of the microwave drying process of coconut kernel. The mass loading has an impact on the drying process at low microwave powers and high mass loadings. A new parameter, MPML, can be defined to identify the critical initial mass loading for a given material at a given microwave power. For drying of coconut kernel with circulating air flow velocity of 1.0 $ms^{-1}$, the MPML value is around 3.7 $Wg^{-1}$. However, further studies are required to generalize the application of MPML for the microwave assisted air drying of food materials.

### 4.2 Mathematical Modelling of Drying Curves

Regression analysis was carried out for the data of 15 experiments listed in Table 3.3 using 7 selected empirical drying models stated in Table 2.2. The results of the statistical analysis are given in Tables 4.1 to 4.7.

1. Newtons Model: $MR = e^{-kt}$

*Table 4.1 Newton model curve fitting results*

| | | 100 W | | | | | 180 W | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter | 20 g | 40 g | 60 g | 80 g | 100 g | 20 g | 40 g | 60 g | 80 g | 100 g |
| Cons | k | 0.008 | 0.007 | 0.007 | 0.007 | 0.005 | 0.012 | 0.01115 | 0.012 | 0.0146 | 0.009 |
| Stat. | SSE | 0.1470 | 0.3095 | 0.2514 | 0.1797 | 0.1247 | 0.0426 | 0.2202 | 0.1872 | 0.15123 | 0.12461 |
| | $R^2$ | 0.8910 | 0.8450 | 0.8724 | 0.8693 | 0.9028 | 0.9398 | 0.8724 | 0.8525 | 0.89688 | 0.9124 |
| | Adjusted $R^2$ | 0.8910 | 0.8450 | 0.8724 | 0.8693 | 0.9028 | 0.9398 | 0.8724 | 0.8525 | 0.89688 | 0.9123 |
| | RMSE | 0.0700 | 0.0839 | 0.0813 | 0.0865 | 0.0706 | 0.0473 | 0.0733 | 0.0803 | 0.07484 | 0.07060 |
| | | 300 W | | | | | | | | | |
| | Parameter | 40 g | 60 g | 80 g | 100 g | 200 g | | | | | |
| Cons | k | 0.0245 | 0.02939 | 0.02928 | 0.02486 | 0.01541 | | | | | |
| Stat. | SSE | 0.0292 | 0.0302 | 0.0319 | 0.0240 | 0.0559 | | | | | |
| | $R^2$ | 0.9717 | 0.9746 | 0.9622 | 0.9694 | 0.9649 | | | | | |
| | Adjusted $R^2$ | 0.9717 | 0.9746 | 0.9622 | 0.9694 | 0.9649 | | | | | |
| | RMSE | 0.0415 | 0.0409 | 0.0477 | 0.0414 | 0.0455 | | | | | |

2. Page model: $MR = e^{-kt^n}$

*Table 4.2 Page model curve fitting results*

| | | 100 W | | | | | 180 W | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter | 20 g | 40 g | 60 g | 80 g | 100 g | 20 g | 40 g | 60 g | 80 g | 100 g |
| Const. | k | 0.0376 | 0.0433 | 0.04 | 0.043 | 0.0318 | 0.0381 | 0.05926 | 0.0619 | 0.0574 | 0.04003 |
| | n | 0.7232 | 0.6749 | 0.6912 | 0.6794 | 0.6827 | 0.7445 | 0.6625 | 0.6882 | 0.714 | 0.7228 |
| Stat. | SSE | 0.0052 | 0.0047 | 0.0109 | 0.0217 | 0.0033 | 0.0008 | 0.0028 | 0.0058 | 0.00495 | 0.00083 |
| | $R^2$ | 0.9977 | 0.9977 | 0.9945 | 0.9842 | 0.9975 | 0.9989 | 0.9984 | 0.9954 | 0.99663 | 0.9994 |
| | Adjusted $R^2$ | 0.9977 | 0.9976 | 0.9943 | 0.9835 | 0.9974 | 0.9988 | 0.9984 | 0.9952 | 0.99650 | 0.99939 |
| | RMSE | 0.0120 | 0.0104 | 0.0171 | 0.0307 | 0.0116 | 0.0067 | 0.0083 | 0.0144 | 0.01380 | 0.00589 |
| | | 300 W | | | | | | | | | |
| | Parameter | 40 g | 60 g | 80 g | 100 g | 200 g | | | | | |
| Const. | k | 0.0696 | 0.05747 | 0.0718 | 0.05621 | 0.03507 | | | | | |
| | n | 0.8486 | 0.8771 | 0.781 | 0.8178 | 0.8514 | | | | | |
| Stat. | SSE | 0.0035 | 0.0008 | 0.0046 | 0.0007 | 0.0072 | | | | | |
| | $R^2$ | 0.9966 | 0.9993 | 0.9945 | 0.9992 | 0.9955 | | | | | |
| | Adjusted $R^2$ | 0.9964 | 0.9993 | 0.9941 | 0.9991 | 0.9953 | | | | | |
| | RMSE | 0.0148 | 0.0068 | 0.0189 | 0.0071 | 0.0167 | | | | | |

3. Henderson and Pabis model: $MR = a.e^{-kt}$

*Table 4.3Henderson Pabis model curve fitting results*

| | | 100 W | | | | | 180 W | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter | 20 g | 40 g | 60 g | 80 g | 100 g | 20 g | 40 g | 60 g | 80 g | 100 g |
| Const. | k | 0.0071 | 0.0054 | 0.0058 | 0.0067 | 0.0043 | 0.0109 | 0.009418 | 0.0102 | 0.01168 | 0.00747 |
| | a | 0.8659 | 0.8208 | 0.8452 | 1 | 0.8755 | 0.9139 | 0.8284 | 0.8371 | 0.8501 | 0.865 |
| Stat. | SSE | 0.0533 | 0.1039 | 0.2448 | 0.1220 | 0.0541 | 0.0152 | 0.0736 | 0.0847 | 0.0744 | 0.0433 |
| | $R^2$ | 0.9605 | 0.9480 | 0.8758 | 0.9112 | 0.9578 | 0.9785 | 0.9573 | 0.9332 | 0.9493 | 0.9696 |
| | Adjusted $R^2$ | 0.9591 | 0.9467 | 0.8758 | 0.9074 | 0.9561 | 0.9773 | 0.9563 | 0.9308 | 0.9473 | 0.9683 |
| | RMSE | 0.0429 | 0.0492 | 0.0803 | 0.0728 | 0.0475 | 0.0291 | 0.0429 | 0.0550 | 0.0535 | 0.0425 |

| | | 300 W | | | | |
|---|---|---|---|---|---|---|
| | Parameter | 40 g | 60 g | 80 g | 100 g | 200 g |
| Const. | k | 0.02312 | 0.02883 | 0.0264 | 0.02392 | 0.01488 |
| | a | 0.9267 | 0.9307 | 0.9324 | 0.9348 | 0.9221 |
| Stat. | SSE | 0.0149 | 0.0150 | 0.0224 | 0.0115 | 0.02392 |
| | $R^2$ | 0.9855 | 0.9874 | 0.9735 | 0.9853 | 0.9348 |
| | Adjusted $R^2$ | 0.9846 | 0.9867 | 0.9714 | 0.9842 | 0.02392 |
| | RMSE | 0.0306 | 0.0297 | 0.0415 | 0.0298 | 0.9348 |

4. Logarithmic drying model : $MR = a.e^{-kt} + c$

*Table 4.4 Logarithmic drying model curve fitting results*

| | | 100 W | | | | | 180 W | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter | 20 g | 40 g | 60 g | 80 g | 100 g | 20 g | 40 g | 60 g | 80 g | 100 g |
| Const. | k | 0.0145 | 0.0113 | 0.0119 | 0.0132 | 0.0104 | 0.0193 | 0.01682 | 0.0220 | 0.02172 | 0.01255 |
| | a | 0.7206 | 0.7195 | 0.7454 | 0.7956 | 0.7059 | 0.72 | 0.7499 | 0.7321 | 0.7821 | 0.7608 |
| | c | 0.2215 | 0.1938 | 0.1899 | 0.1794 | 0.249 | 0.2357 | 0.1579 | 0.2088 | 0.1606 | 0.1596 |
| Stat. | SSE | 0.0120 | 0.0287 | 0.0252 | 0.0118 | 0.0073 | 0.0057 | 0.0280 | 0.0155 | 0.0161 | 0.0135 |
| | $R^2$ | 0.9911 | 0.9856 | 0.9872 | 0.9914 | 0.9943 | 0.9919 | 0.9838 | 0.9878 | 0.9890 | 0.9905 |
| | Adjusted $R^2$ | 0.9905 | 0.9849 | 0.9865 | 0.9907 | 0.9938 | 0.9909 | 0.9830 | 0.9869 | 0.9882 | 0.9897 |
| | RMSE | 0.0207 | 0.0261 | 0.0265 | 0.0231 | 0.0178 | 0.0184 | 0.0268 | 0.0239 | 0.0254 | 0.0243 |

| | | 300 W | | | | |
|---|---|---|---|---|---|---|
| | Parameter | 40 g | 60 g | 80 g | 100 g | 200 g |
| Const. | k | 0.02972 | 0.03759 | 0.04417 | 0.03617 | 0.01961 |
| | a | 0.8655 | 0.8873 | 0.8251 | 0.8219 | 0.8666 |
| | c | 0.0902 | 0.08122 | 0.1691 | 0.1541 | 0.09275 |
| Stat. | SSE | 0.0100 | 0.0047 | 0.0009 | 0.0033 | 0.0165 |
| | $R^2$ | 0.9903 | 0.9961 | 0.9989 | 0.9958 | 0.9897 |
| | Adjusted $R^2$ | 0.9890 | 0.9956 | 0.9988 | 0.9951 | 0.9888 |
| | RMSE | 0.0259 | 0.0171 | 0.0087 | 0.0166 | 0.0257 |

5. Midilli et al. model : $MR = e^{-kt^{n}} + bt$

*Table 4.5 Midilli et al. model curve fitting results*

| | | 100 W | | | | | 180 W | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter | 20 g | 40 g | 60 g | 80 g | 100 g | 20 g | 40 g | 60 g | 80 g | 100 g |
| Const. | k | 0.03768 | 0.0465 | 0.0362 | 0.0303 | 0.0929 | 0.0437 | 0.08613 | 0.0679 | 0.06959 | 0.04367 |
| | n | 2.06E-12 | 0.6263 | 0.6923 | 0.7516 | 0.486 | 0.6806 | 0.5447 | 0.6324 | 0.639 | -1.92E-05 |
| | B | 0.7232 | 4.50E-05 | 0.0001 | 0.0002 | 9.82E-06 | -0.0003 | -0.000272 | 0.0002 | 6.66E-05 | 0.6638 |
| Stat. | SSE | 0.0052 | 0.0045 | 0.0093 | 0.0110 | 0.0006 | 0.0006 | 0.0008 | 0.0016 | 0.0013 | 0.0006 |
| | $R^2$ | 0.9977 | 0.9977 | 0.9953 | 0.9920 | 0.9992 | 0.9992 | 0.9995 | 0.9987 | 0.9991 | 0.9996 |
| | Adjusted $R^2$ | 0.9977 | 0.9976 | 0.9950 | 0.9913 | 0.9991 | 0.9991 | 0.9995 | 0.9986 | 0.9990 | 0.9995 |
| | RMSE | 0.0120 | 0.0104 | 0.0161 | 0.0224 | 0.0053 | 0.0058 | 0.0045 | 0.0077 | 0.0072 | 0.0053 |

| | | 300 W | | | | |
|---|---|---|---|---|---|---|
| | Parameter | 40 g | 60 g | 80 g | 100 g | 200 g |
| Const. | k | 0.06886 | 0.06818 | 0.04543 | 0.07895 | 0.04496 |
| | n | 0.06886 | 0.7855 | 0.9336 | 0.6614 | 0.04496 |
| | b | -0.0008057 | 4.84E-06 | 0.001752 | -0.001024 | -0.0002559 |
| Stat. | SSE | 0.0027 | 0.0005 | 0.0006 | 0.0003 | 0.0075 |
| | $R^2$ | 0.9974 | 0.9996 | 0.9993 | 0.9996 | 0.9953 |
| | Adjusted $R^2$ | 0.9971 | 0.9996 | 0.9992 | 0.9995 | 0.9949 |
| | RMSE | 0.0134 | 0.0054 | 0.0070 | 0.0053 | 0.0173 |

6. Approximation of Diffusion : $MR = a.e^{-kt} + (1-a).e^{-kbt}$

*Table 4.6 Approximation of Diffusion model curve fitting results*

| | | 100 W | | | | | 180 W | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter | 20 g | 40 g | 60 g | 80 g | 100 g | 20 g | 40 g | 60 g | 80 g | 100 g |
| Const. | k | 0.06048 | 0.0517 | 0.0332 | 0.022 | 0.0307 | 0.1112 | 0.07448 | 0.0647 | 0.06599 | 0.1154 |
| | a | 0.2714 | 0.3229 | 0.4113 | 0.6092 | 0.3496 | 0.1736 | 0.3372 | 0.3939 | 0.3742 | 0.2151 |
| | b | 0.1176 | 0.1096 | 0.1499 | 0.1546 | 0.12 | 0.0903 | 0.1095 | 0.1465 | 0.1573 | 0.07231 |
| Stat. | SSE | 0.0029 | 0.0032 | 0.0025 | 0.0013 | 0.0021 | 0.0006 | 0.0005 | 0.0006 | 0.0006 | 0.0033 |
| | $R^2$ | 0.9987 | 0.9984 | 0.9987 | 0.9991 | 0.9984 | 0.9991 | 0.9997 | 0.9995 | 0.9996 | 0.9987 |
| | Adjusted $R^2$ | 0.9986 | 0.9983 | 0.9986 | 0.9990 | 0.9982 | 0.9990 | 0.9997 | 0.9995 | 0.9995 | 0.9985 |
| | RMSE | 0.0092 | 0.0087 | 0.0084 | 0.0076 | 0.0096 | 0.0060 | 0.0035 | 0.0048 | 0.0051 | 0.0119 |

| | | 300 W | | | | |
|---|---|---|---|---|---|---|
| | Parameter | 40 g | 60 g | 80 g | 100 g | 200 g |
| Const. | k | 0.2853 | 0.181 | 0.05802 | 0.1492 | 0.08406 |
| | a | 0.14 | 0.1503 | 0.659 | 0.1864 | 0.1864 |
| | b | 0.1264 | 0.177 | 0.2342 | 0.1564 | 0.1847 |
| Stat. | SSE | 0.0023 | 0.0005 | 0.0007 | 0.0003 | 0.0091 |
| | $R^2$ | 0.998 | 0.9985 | 0.9992 | 0.9997 | 0.998 |
| | Adjusted $R^2$ | 0.9985 | 0.9983 | 0.9991 | 0.9996 | 0.9945 |
| | RMSE | 0.0123 | 0.0054 | 0.0075 | 0.0047 | 0.0191 |

7. Verma et al. : $MR = a.e^{-kt} + (1-a).e^{-gt}$

*Table 4.7 Verma et al. model curve fitting results*

| | | 100 W | | | | | 180 W | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Parameter | 20 g | 40 g | 60 g | 80 g | 100 g | 20 g | 40 g | 60 g | 80 g | 100 g |
| Cons t. | k | 0.04865 | 0.0038 | 0.0295 | 0.0023 | 0.0263 | 0.1069 | 0.06928 | 0.0548 | 0.007311 | 0.06671 |
| | a | 0.3113 | 0.6372 | 0.4372 | 0.4042 | 0.3785 | 0.1832 | 0.3484 | 0.4324 | 0.579 | 0.2781 |
| | g | 0.00516 | 0.0406 | 0.0034 | 0.0214 | 0.0027 | 0.0090 | 0.007074 | 0.0059 | 0.05701 | 0.00585 |
| Stat. | SSE | 0.0021 | 0.0032 | 0.0025 | 0.0013 | 0.0021 | 0.0006 | 0.0005 | 0.0006 | 0.0006 | 0.0033 |
| | $R^2$ | 0.9984 | 0.9984 | 0.9987 | 0.9991 | 0.9984 | 0.9991 | 0.9997 | 0.9995 | 0.9996 | 0.9977 |
| | Adjusted $R^2$ | 0.9983 | 0.9983 | 0.9986 | 0.9990 | 0.9982 | 0.9990 | 0.9997 | 0.9995 | 0.9995 | 0.9975 |
| | RMSE | 0.0087 | 0.0087 | 0.0084 | 0.0076 | 0.0096 | 0.0060 | 0.0035 | 0.0048 | 0.0051 | 0.0119 |

| | | 300 W | | | | |
|---|---|---|---|---|---|---|
| | Parameter | 40 g | 60 g | 80 g | 100 g | 200 g |
| Const. | k | 0.1474 | 0.1053 | 0.05266 | 0.1206 | 0.01193 |
| | a | 0.199 | 0.2971 | 0.6928 | 0.2286 | 0.7448 |
| | g | 0.01967 | 0.0223 | 0.007224 | 0.01912 | 0.06732 |
| Stat. | SSE | 0.0023 | 0.0005 | 0.0007 | 0.0003 | 0.0047 |
| | $R^2$ | 0.9978 | 0.9996 | 0.9992 | 0.9997 | 0.9970 |
| | Adjusted $R^2$ | 0.9975 | 0.9996 | 0.9991 | 0.9996 | 0.9968 |
| | RMSE | 0.0123 | 0.0054 | 0.0075 | 0.0047 | 0.0137 |

The results of the regression analysis indicated that the Approximation of Diffusion model best described the experimental results of the drying curves for coconut kernel. This was concluded on the basis of $R^2$ being over 0.998 in all the cases and SSE (<0.0091) and RMSE (<0.0191) being considerably small displaying very good fit. It was further observed that other models such as Verma et al. model, Midilli et al. model Logarithmic drying model and the Page model also showed very good statistical compatibility with the experimental data obtained from drying experiments.

The most suitable model was selected by identifying the model with the highest statistical conformation and lowest degree of freedom for curve fitting. Based on this criterion, Page model with only 2 variables was selected as the best model for describing the drying kinetics of microwave assisted drying of coconut kernel. The $R^2$ for all the experimental data was within range of (0.9842 - 0.9994) while Sum of square error (SSE) was (0. 0007 - 0.0217) and Root mean square error (RMSE) was (0. 00589 - 0.0307).

### 4.2.1 Development of a new model

Henceforth, the Page model was considered for further study to determine the model constants as a function of microwave power. Since only microwave power was considered, the effects of mass loading were minimized by selecting experimental data representing MPML greater than 3.7 $Wg^{-1}$.

Based on the Page model that has two model constants, 16 equations were developed as per the maximum number of combinations by considering generic; (a) Linear, (b) Quadratic, (c) Logarithmic and (d) Arrhenius type equations for the two model constants. The 16 combinations are summarized in Table 4.8 and Table 4.9.

*Table 4.8 Generic types of functions used to substitute for the model constants k and n of Page mode*

| $MR = e^{-kt^n}$ | k | n |
|---|---|---|
| Linear | $a_1P + b_1$ | $a_2P + b_2$ |
| Quadratic | $a_1P^2 + b_1P + C_1$ | $a_2P^2 + b_2P + C_2$ |
| Logarithmic | $a_1\log(b_1P)$ | $a_2\log(b_2P)$ |
| Arrhenius type | $a_1\exp(\frac{b_1}{RP})$ | $a_2\exp(\frac{b_2}{RP})$ |

*Table 4.9 The 16 possible combinations of models derived from the Page model*

| | |
|---|---|
| $MR = e^{-(a_1P+b_1)t^{(a_2P+b_2)}}$<br>$MR = e^{-(a_1P+b_1)t^{(a_2P^2+b_2P+C_2)}}$<br>$MR = e^{-(a_1P+b_1)t^{(a_2\log(b_2P))}}$<br>$MR = e^{-(a_1P+b_1)t^{(a_2\exp(\frac{b_2}{RP}))}}$ | $MR = e^{-(a_1P^2+b_1P+C_1)t^{(a_2P+b_2)}}$<br>$MR = e^{-(a_1P^2+b_1P+C_1)t^{(a_2P^2+b_2P+C_2)}}$<br>$MR = e^{-(a_1P^2+b_1P+C_1)t^{(a_2\log(b_2P))}}$<br>$MR = e^{-(a_1P^2+b_1P+C_1)t^{(a_2\exp(\frac{b_2}{RP}))}}$ |
| $MR = e^{-(a_1\log(b_1P))t^{(a_2P+b_2)}}$<br>$MR = e^{-(a_1\log(b_1P))t^{(a_2P^2+b_2P+C_2)}}$<br>$MR = e^{-(a_1\log(b_1P))t^{(a_2\log(b_2P))}}$<br>$MR = e^{-(a_1\log(b_1P))t^{(a_2\exp(\frac{b_2}{RP}))}}$ | $MR = e^{-(a_1\exp(\frac{b_1}{RP}))t^{(a_2P+b_2)}}$<br>$MR = e^{-(a_1\exp(\frac{b_1}{RP}))t^{(a_2P^2+b_2P+C_2)}}$<br>$MR = e^{-(a_1\exp(\frac{b_1}{RP}))t^{(a_2\log(b_2P))}}$<br>$MR = e^{-(a_1\exp(\frac{b_1}{RP}))t^{(a_2\exp(\frac{b_2}{RP}))}}$ |

Multiple regression analysis on the experimental data against the 16 modified Page equations were carried out to develop a correlation between moisture ratio (*MR*), time (*t*) and Microwave power (*P*).

Based on a multivariate regression analysis the following generalised drying equation (*Equation 4.1*) was developed to predict the total drying time and moisture ratio for the microwave powers of 100 W, 180 W and 300 W.

$$MR = \exp(\,a.exp\left(\frac{-b}{R.P}\right).t^{(c.P+0.6)}) \quad ;\ \textit{Equation 4.1}$$

Where, R=8.314 $Jmol^{-1}K^{-1}$; a= -0.07 $min^{-1}$; b= 310 $J^2mol^{-1}K^{-1}s^{-1}$; c = 0.0007 $sJ^{-1}$

Since R is the universal gas constant and b is constant for the given experimental condition, a new parameter M can be defined such that;

$$M = \frac{-b}{R} \cong -37.29\,Js^{-1}$$

Therefore, equation 4.1 can be written as;

$$MR = exp(\,a.exp\left(\frac{M}{P}\right).t^{(c.P+0.6)}) \ ;\ \textit{Equation 4.2}$$

Where, a= -0.07 $min^{-1}$, M=37.29 $Js^{-1}$ and c = 0.0007 $sJ^{-1}$. Parameter *t* (time) needs to be substituted in mins and *P* in W.

Based on the Equation 4.2, the following results were obtained to compare the predicted results with the actual experimental data and statistical fitting parameters of $R^2$, reduced chi-square ($\varkappa^2$) and root mean square error (RMSE) for microwave powers of 100 W, 180 W and 300 W.

- When supplied magnetron microwave power = 100 W;

$$MR = \exp(-0.04821.t^{0.67})$$

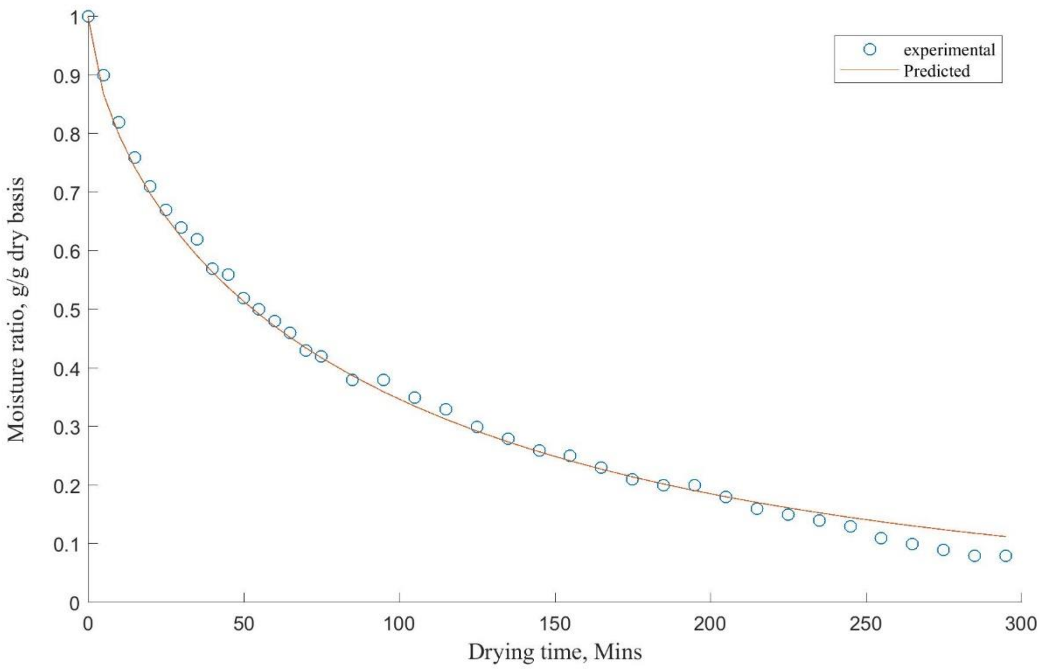



*Figure 4.7 Drying of coconut kernel at 100 W output microwave power experimental results and predicted results*

The $R^2$, reduced chi-square ($\varkappa^2$) and root mean square error (RMSE) of the experimental data vs. the model predicted data were 0.998652, 0.00000314 and 0.01771 respectively. The predicted results using the developed model were in good agreement with the experimental results for the microwave power of 100 W.

- When supplied magnetron microwave power = 180 W;

$$MR = \exp(-0.0569.t^{0.726})$$

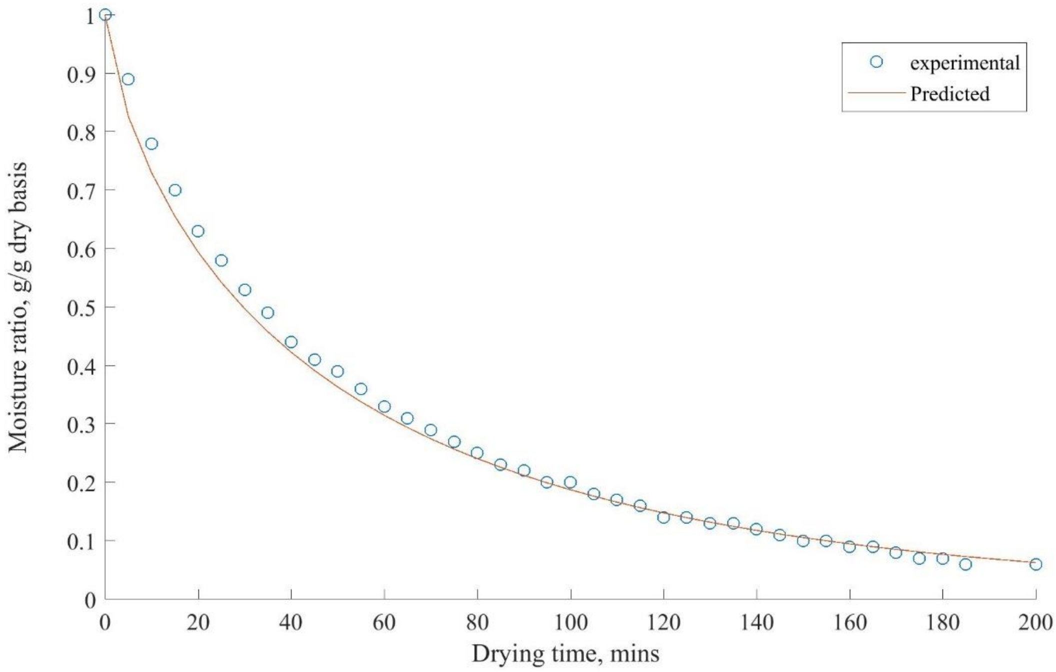



*Figure 4.8 Drying of coconut kernel at 180 W output microwave power experimental results and predicted results*

The $R^2$, reduced chi-square ($\chi^2$) and root mean square error (RMSE) of the experimental data vs. the model predicted data were 0.999266, 0.00000322 and 0.0173858 respectively. The predicted results using the developed model were in good agreement with the experimental results for the microwave power supplied of 180 W.

- When supplied magnetron microwave power = 300 W;

$$MR = \exp(-0.06182.t^{0.81})$$

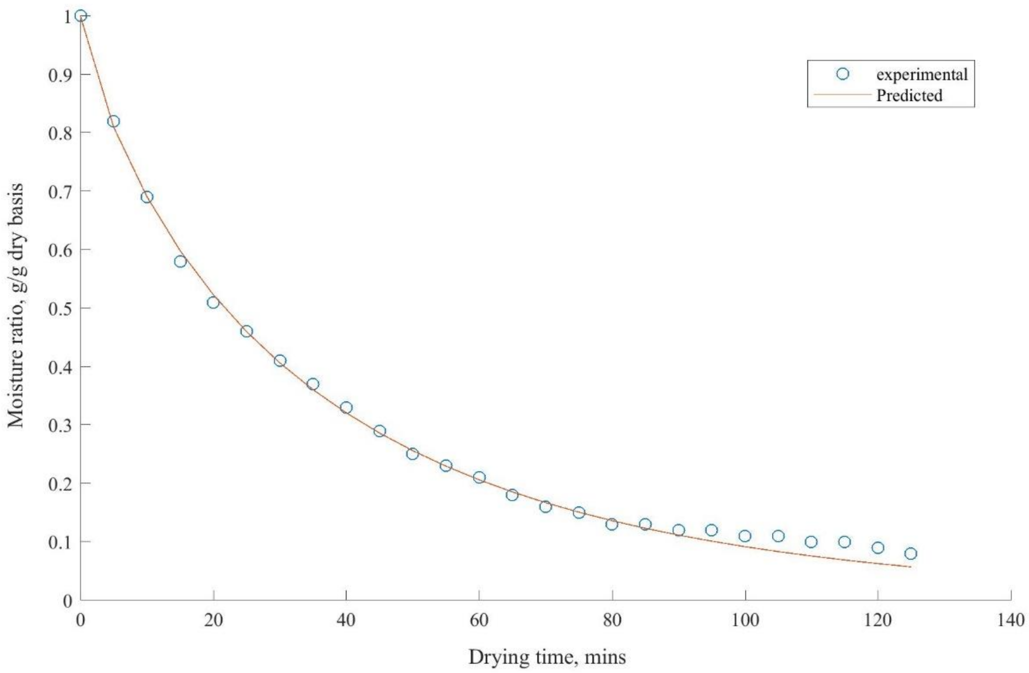



*Figure 4.9 Drying of coconut kernel at 300 W output microwave power experimental results and predicted results*

The $R^2$, reduced chi-square ($\varkappa^2$) and root mean square error (RMSE) of the experimental data vs. the model predicted data were 0.999266, 0.00000322 and 0.0173858 respectively. The predicted results using the developed model were in good agreement with the experimental results for the microwave power of 300 W.

### 4.3 Effective Moisture Diffusivity

The effective diffusivity was calculated based on the graphs plotted using equation 2.12. The parameter L, refers to the half thickness of the drying material, which is 5±1mm. Effective diffusivity $D_{eff}$ is found in $m^2s^{-1}$ using the gradient of the graphs (Figure 4.10).

The effective diffusivity values of drying data when MPML was equal to or larger than 3.7 $Wg^{-1}$ is given in Table 4.10.

*Table 4.10 Calculated effective diffusivity values*

| Power (W) | Mass loading (g) | Effective Diffusivity ($m^2s^{-1}$) | $D_{eff}/power$ ($m^2s^{-1}W^{-1}$) |
|---|---|---|---|
| 100 W | 20 g | 1.31 X $10^{-9}$ | 1.31 X $10^{-11}$ |
| 180 W | 20 g | 2.37 X $10^{-9}$ | 1.31 X $10^{-11}$ |
| 180 W | 40 g | 2.34 X $10^{-9}$ | 1.30 X $10^{-11}$ |
| 300 W | 40 g | 3.99 X $10^{-9}$ | 1.33 X $10^{-11}$ |
| 300 W | 60 g | 4.00 X $10^{-9}$ | 1.33 X $10^{-11}$ |
| 300 W | 80 g | 4.00 X $10^{-9}$ | 1.33 X $10^{-11}$ |

The effective diffusivity values of drying data when the MPML was lesser than 3.7 $Wg^{-1}$ are given in Table 4.11.

*Table 4.11 Calculated effective diffusivity values*

| Power (W) | Mass loading (g) | Effective Diffusivity ($m^2s^{-1}$) | $D_{eff}/power$ ($m^2s^{-1}W^{-1}$) |
|---|---|---|---|
| 100 W | 40 g | 1.10 X $10^{-9}$ | 1.10 X $10^{-11}$ |
| 100 W | 60 g | 1.07 X $10^{-9}$ | 1.07 X $10^{-11}$ |
| 100 W | 80 g | 9.84 X $10^{-10}$ | 9.84 X $10^{-12}$ |
| 100 W | 100 g | 8.02 X $10^{-10}$ | 8.02 X $10^{-12}$ |
| 180 W | 60 g | 1.96 X $10^{-9}$ | 1.09 X $10^{-11}$ |
| 180 W | 80 g | 1.84 X $10^{-9}$ | 1.02 X $10^{-11}$ |
| 180 W | 100 g | 1.72 X $10^{-9}$ | 9.60 X $10^{-12}$ |
| 300 W | 100 g | 3.41 X $10^{-9}$ | 1.13 X $10^{-11}$ |

It can be deduced that a common factor for $D_{eff}/power$ can be defined when the MPML value is in excess of 3.7 $Wg^{-1}$ for the microwave assisted drying of coconut kernel. The value of this factor is approximated to $1.3 \times 10^{-11}$ $m^2s^{-1}W^{-1}$ and it can be used to calculate the effective diffusivity when the supplied microwave power is known. However, this is not applicable to MPML less than 3.7 $Wg^{-1}$ as the initial mass loading also becomes effective. However, these values may depend on the other factors such as shape factors, air velocities and relative humidity, which may have an impact on the rate of drying [63].

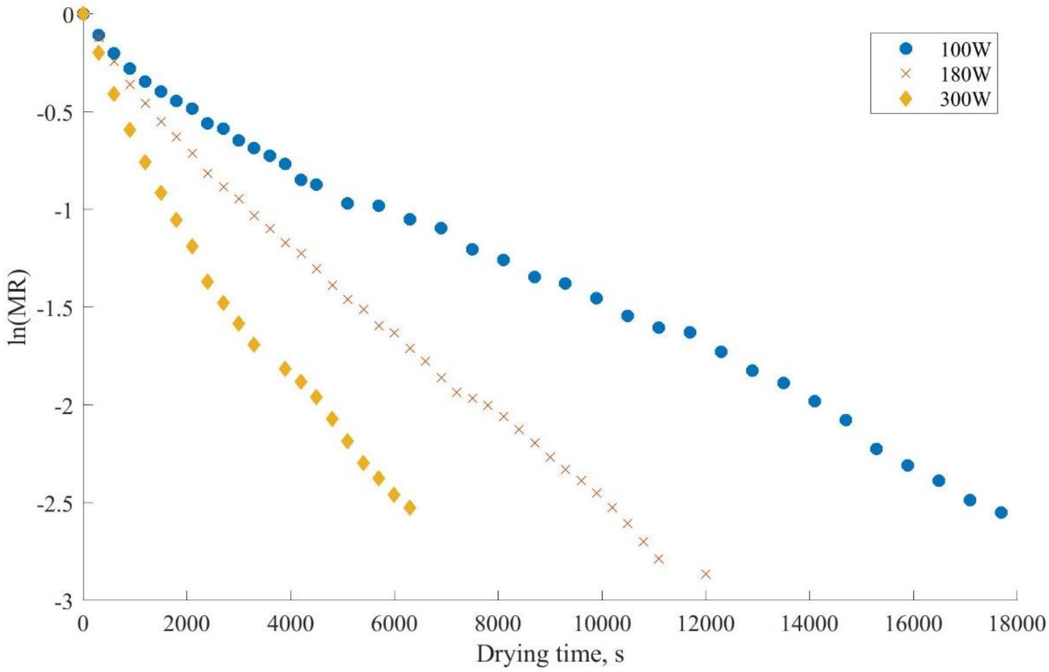



*Figure 4.10 ln(MR) vs time graph used to calculate effective diffusivity for mass loading 60 g*

### 4.4 Drying rates

Typical drying curves for microwave assisted air drying of coconut kernel are shown in Figure 4.11.

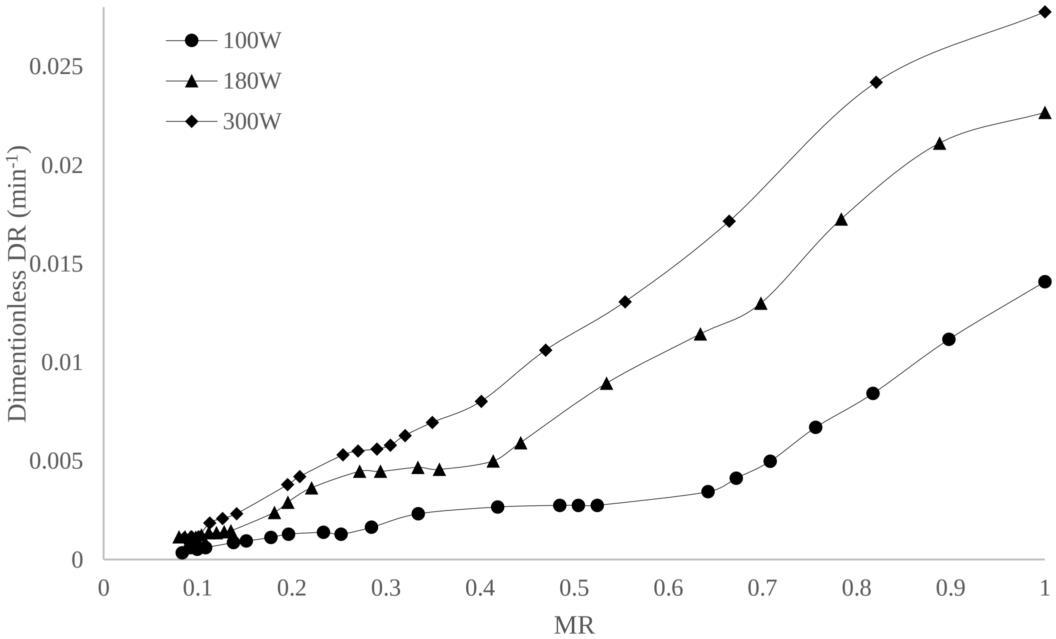



*Figure 4.11 Plot of moisture ratio (MR) vs drying rate (DR)*

The drying rate increases with increased microwave power as expected. A notable increase in drying rate was observed beyond the approximate moisture ratio of 0.35 in all microwave power levels. For an average initial moisture content of 85±5 % (w/w, dry basis), this moisture ratio represents moisture content of 30 % (w/w, dry basis). In previous studies on hot air drying of coconut kernel, the moisture content of around 30 % (w/w, dry basis) was determined as the critical parameter separating the removal of free moisture and bound moisture in the coconut kernel [7].

### 4.5 Dielectric properties of coconut kernel

Based on Sun et al. formula (Equations 2.6 and 2.7) the dielectric properties were calculated for different temperature values that fell within the range of the temperatures from 27 °C to 94 °C as the maximum drying temperature allowable for the production of desiccated coconut according to the SLS 98 (2013 revision) is 95 °C and for the production of virgin coconut oil is 68 °C according to the SLS 32: 2017. The average temperature within the coconut cubes was substituted in Kelvin units. The average initial moisture content and average ash content were found to be 88.4 % (w/w, dry basis) and 0.97 % (w/w, dry basis) respectively for the three samples.

The experiments were repeated three times for a given temperature and average values are given in Table 4.12.

*Table 4.12 Calculated dielectric properties using the formulas suggested by Sun et al and Sipahigolu et al.*

| **Temperature in °C** | **Sun et al. formula** | |
|---|---|---|
| | **Dielectric constant $\varepsilon'$** | **Loss factor $\varepsilon''$** |
| 27 | 44.3983 | 3.79954 |
| 36 | 44.3853 | 3.79266 |
| 44 | 44.3723 | 3.78923 |
| 53.5 | 44.3567 | 3.78882 |
| 61.25 | 44.3439 | 3.79084 |
| 69 | 44.3313 | 3.79606 |
| 72 | 44.3264 | 3.7988 |
| 78.5 | 44.3157 | 3.80608 |
| 83 | 44.3084 | 3.81222 |
| 89.5 | 44.2978 | 3.82267 |
| 94 | 44.2904 | 3.831 |

The results given in Table 4.12 and Figure 4.12 indicate constant values for the dielectric constant and the loss factor for the operating range of temperatures. Therefore, the average values for dielectric constant and loss factor were selected as 44.4 and 3.8 for drying of coconut kernel within the temperature range of 27 – 94 ºC.

In an article published by Sipahioglu et al. in the journal of food science, the authors have compared dielectric constants of many fruits and vegetables over a temperature range of 5 - 130 ºC. Many vegetables such as carrots, cucumber, radish, broccoli, and fruits such as banana, pear and apple displayed a reduction in dielectric constant when the temperature was increased. However, some vegetables such as, potato, yam, garlic and spinach displayed different behaviours as in the case of coconut [45].

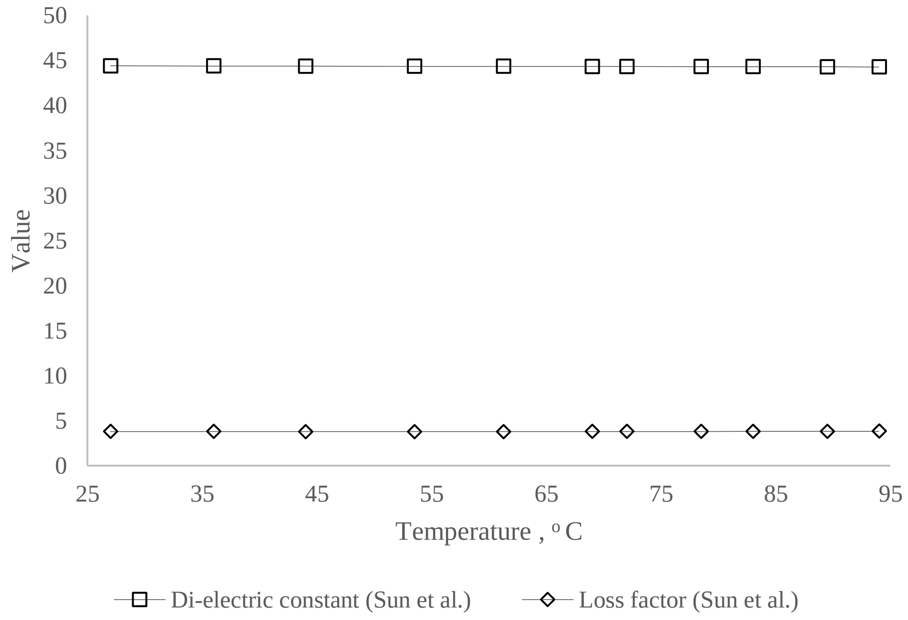



*Figure 4.12 Dielectric properties change with time of coconut*

The constant dielectric properties of coconut over the operating temperature range of 27 – 94 ºC may be due to the presence of hydrophilic compounds similar to the case observed in garlic [45]. The dielectric constant of garlic was approximately constant over the temperature ranges of 10 – 70 ºC and the reason was identified as the presence of hydrophilic compounds such as inulin and pectin. On the other hand, the rigid structure of coconut meat can maintain a consistent absorption and conversion of microwave energy into heat. Similar behaviour was also observed in potato, where the dielectric constant of potato was constant at around 36.5 over the temperature range of

20 – 65 ºC. However, the dielectric constant suddenly increased to 44 at around 70 ºC which was mainly attributed to the gelatinization of potato [45].

Moreover, the mass percentages of water and ash content, were factored in the Equations 2.6 and 2.7, proposed by Sun et al [60]. It has to be noted that ash content has a significant influence on the loss factor and is a very good indicator of the presence of salts in coconut. Salts can significantly reduce the dielectric constant as it is able to bind water molecules [45].

### 4.6 Shrinkage of microwave drying of coconut

Figure 4.13 shows the comparison of the experimental shrinkage data of microwave assisted air drying of coconut and the ideal shrinkage based on model proposed by Madiouli et al [19]. In the case of microwave drying the shrinkage, occurring was above the ideal shrinkage indicating a considerable structural stability of coconut meat during the drying process. Further, the experimental shrinkage being higher than the ideal shrinkage is an indication that the porosity of the coconut meat increases as the moisture ratio reduces [19]. The linearized shrinkage with moisture ratio for the experimental data was obtained based on curve fitting as, $S = 0.5464MR + 0.4602$.

In comparison, Figure 4.14 shows the shrinkage behaviour of coconut in hot air drying at 60 ºC. The linearized shrinkage with moisture ratio for hot air drying was obtained based on curve fitting as, $S = 0.4616MR + 0.5493$. In both cases, the maximum shrinkage achieved was around 0.55 ($v/v_0$). However, the gradients of the two different linear variations suggest that the shrinkage behaviour is different for the two drying techniques. This observation is further clarified in Figure 4.15, where both data are presented in the same graph. Figure 4.15 depicts that the variation of shrinkage against MR is more uniform in microwave assisted air drying. In the case of hot air drying, the variation was found to be similar to MW assisted air drying at the initial stage of drying (MR from 1.0 to about 0.48). However, a significant difference in the variation of shrinkage behaviour could be observed below the moisture ratio around 0.48. This may be attributed to the structural collapses associated with the removal of bound moisture.

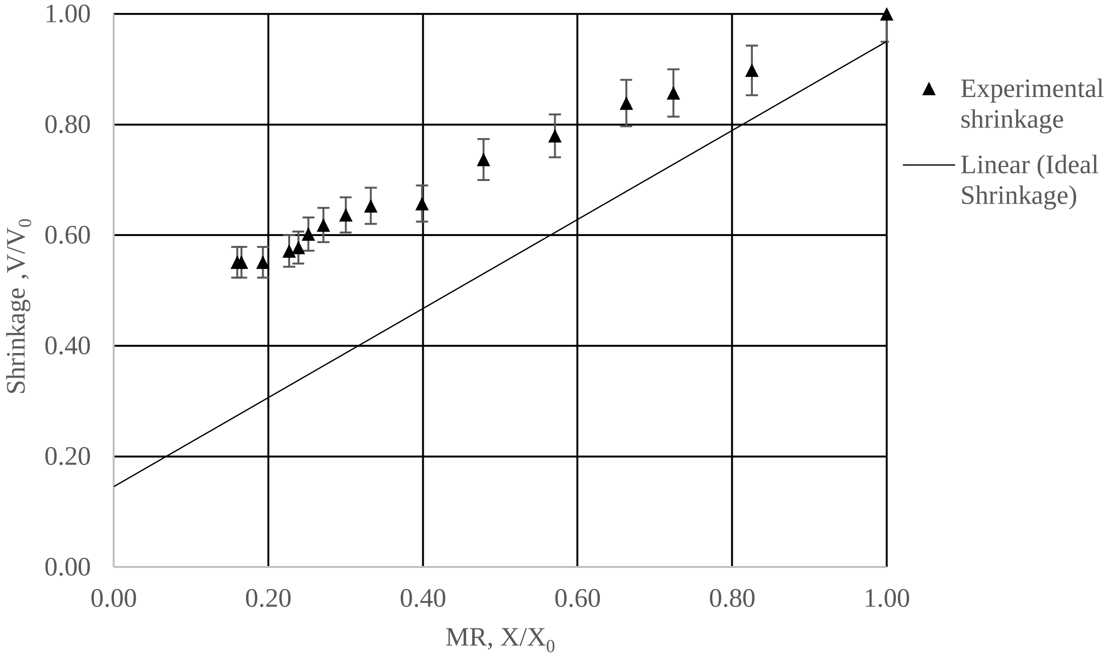



*Figure 4.13 MR vs Shrinkage curve for microwave drying of coconut meat*

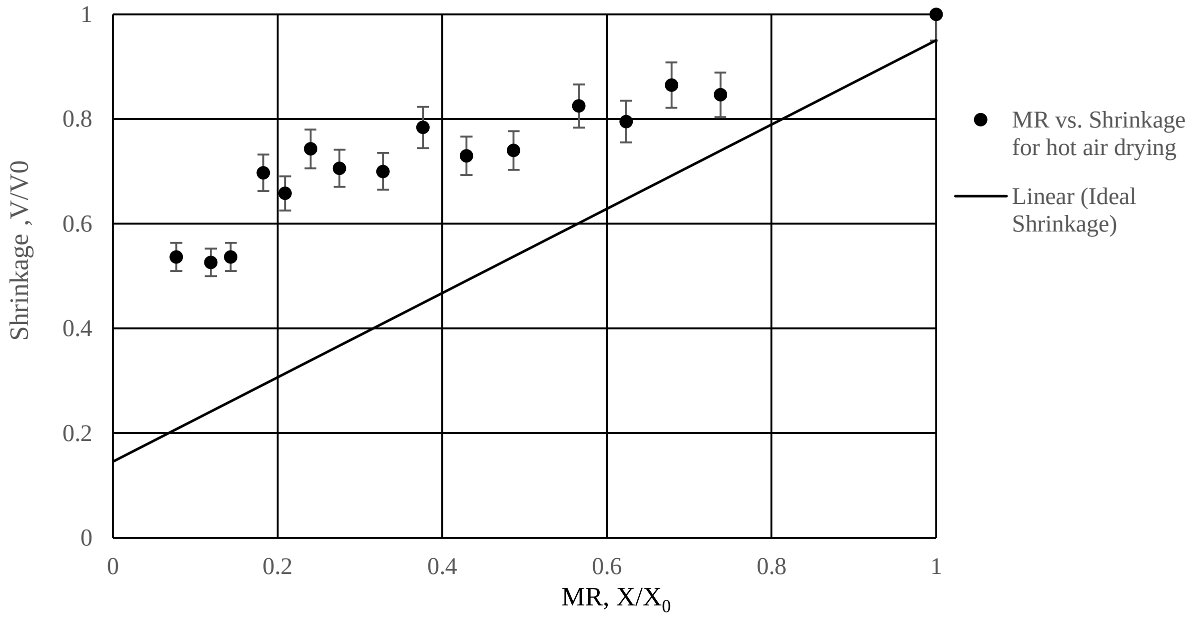



*Figure 4.14 MR vs. Shrinkage of hot air drying of coconut*

In a comprehensive review article Mahiuddin et al. noted the change of shrinkage behaviour during removal of free water and intracellular water (bound water) [64]. In a more recently published article, Khan et al. noted that the shrinkage tends to steepen when food tissue cell walls are ruptured during the mass transfer [65] [66]. With similar arguments, the higher reduction in the volume of the coconut during microwave drying as compared to hot air drying may be explained by the phenomena of higher rate of cell tissue rupture compared to ruptures occurring during hot air drying of coconut. This is in alignment with the distinction of heat transfer mechanisms of the two drying methods

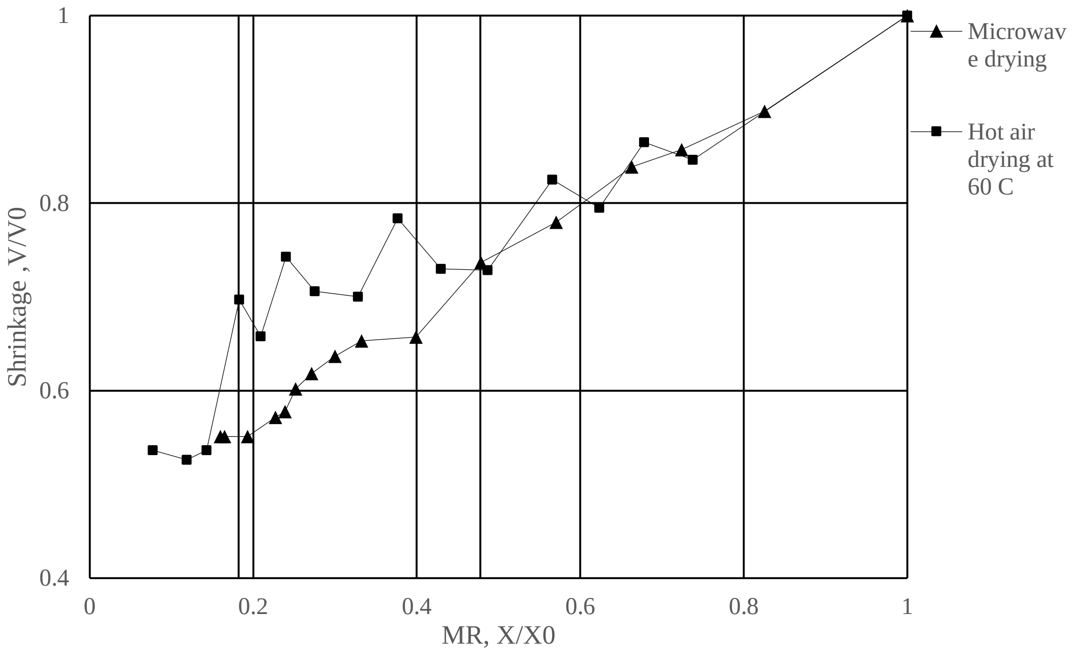



*Figure 4.14 Comparison of shrinkage Vs. MR in hot air drying and microwave drying*

## 4.7 Characterization of dried material for quality aspects

Samples of virgin coconut oil (VCO) extracted from microwave dried coconut flakes were analysed in the laboratory of the Coconut Development Authority of Sri Lanka. The results are summarized in Table 4.13 and the reports are given in Annexure B.

*Table 4.13 Quality results of VCO produced from MW dried coconut meat*

| **No.** | **Parameter** | **Test Method** | **Units** | **Results** | **Requirements of SLS 32: 2017 (VCO)** |
|---|---|---|---|---|---|
| 1 | Colour (25 mm on the Lovibond colour scale) (Y + 5R) | SLS-313-1-2009 | Lovibond colour scale | 0.4 | < 1 |
| 2 | Moisture & other matter volatile at 105 ºC | MOC63U Moisture balance | % | 0.2 | ≤0.2 |
| 3 | Free fatty acids (as lauric acid) | SLS-313-1-2009 | % by mass | 0.03 | ≤0.2 |

Similarly, samples of Microwave dried desiccated coconut flakes were produced using the experimental setup and was analysed in the laboratory of the Coconut Development

Authority of Sri Lanka. The results are summarized in Table 4.14 and the reports are given in Annexure C.

*Table 4.14 Quality results of DC produced from MW dried coconut flakes*

| **No.** | **Parameter** | **Test Method** | **Units** | **Results** | **Requirements of SLS 98: 2013 (DC)** |
|---|---|---|---|---|---|
| 1 | Colour (25 mm on the Lovibond colour scale) | SLS-313-1-2009 | Lovibond colour scale | Y – 1.1<br>B – 0.1<br>R – 0.2 | Y – 0.9<br>B – 0.1<br>R – 0.2 |
| 2 | Moisture & other volatile matter at 105 ºC | MOC63U Moisture balance | % | 1.7 | ≤3 |

Based on the above results it can be concluded that the microwave drying has not hindered the quality of the product. Further optimization should be done to bring down the Y value of DC colour by 0.2 points on the Lovibond colour scale. Though the colour difference cannot be detected by the naked eye and the oil appears as a clear liquid, the deviation can be observed in the test. The reason for the slight yellow colour may be due to non-removal of miniscule fragments of the brown endocarp (testa) of the coconut meat prior to drying [67]. Further, localised burning from microwave drying has the potential to increase the Y and R values of the desiccated coconut. It can be also noted, that the colour of the desiccated coconut is mostly considered for grading purposes rather than a critical parameter for rejection of desiccated coconut [68].

## 4.8 Energy Consumption and Cost Comparison of Microwave Assisted Air Drying

The drying unit operation is one of the most energy intensive processes in many food processing plants. This is due to requirements of heating and removal of moisture, which has a relatively high specific heat capacity when compared to various other materials such as air, glass, sand, ice, ethanol etc.

Cost of microwave drying depends on the energy required to remove the water. Based on the specific heat of water, it can be stated that the energy required to evaporate a given mass of water in a container will be the same despite the mechanism in which the energy is delivered to the water if all the other conditions affecting the process are maintained unchanged. However, this may change if the delivering mechanism has an advantage of reaching the water that needs to be evaporated faster compared to the other mechanism. Microwaves penetrates through coconut tissue and reaches the trapped water almost immediately and has a higher conversion rate to thermal energy by interacting with water molecules combined with the increase in temperature of the water. The increase in temperature however must be controlled in order to meet the required quality standards of DC and VCO.

A gross analysis of the cost of drying can be done based on the required energy and the time for microwave assisted air drying (Figure 2.3) and hot air drying (Figure 2.4). For both cases, the cost of wet coconut (70 % w/w, dry basis) and any other expenses are similar but the electrical power and time for drying are different.

Basis: 1 kg of DC

| | |
|---|---|
| Electricity requirement for hot air drying | = (420 W × 1260 min)/(60 min/hr) |
| | = 8.8 kWh |
| Electricity requirement for MW air drying | = (1300 W × 280 min)/(60 min/hr) |
| | = 6.1 kWh |

A significant reduction of electrical power requirement can be observed in the gross analysis. However, in the industrial practice much cheaper options may be available for hot air generation. Further, the possibility of microwave heating followed by air cooling can be analysed for optimizing the process without compromising the final quality of the dried coconut kernel. This phenomenon is described in section 4.9.

## 4.9 Case study: Rehydration during heating-cooling cycle

According to Sri Lanka standards, the maximum permissible drying temperature for DC is 95 ºC (SLS98:2013) and VCO is 68 ºC (SLS 32: 2017). Hence, continuous microwave assisted air drying cannot be done as the internal temperature of the coconut kernel rises above the maximum stipulated by SLS standards. Therefore, a cycle of microwave heating followed by the air cooling is recommended. However, the rehydration during cooling must be considered in designing the cycle.

Rehydration can be obtained using the Peleg's model [69],

$$M_t = M_0 + \frac{t}{k_1 + k_2 t}$$

where $M_t$ is moisture content at the end of cooling time $t$, $M_0$ is moisture content at the beginning of cooling and $t$ is the cooling time.

**Case study analysis:** Microwave assisted heating at MW powers of 180 W and 300 W was considered along with, cooling using air at room temperature and average air velocity of 1.0 $ms^{-1}$ for drying the coconut cubes (1 $cm^3$) to produce DC was considered. Table 4.15 summarizes the observations and the calculated values of the model constants in Peleg's model.

Other relevant data

Room temperature was 30 ºC.

The maximum permissible temperature in coconut kernel is 95 ºC.

Cooling time and temperature after cooling are 12 minutes and 66 ºC for both cases.

*Table 4.15 Peleg's model parameters Quality results of DC produced from MW dried coconut flakes*

| MW Power (W) | Heating time (min) | Mass of wet coconut (g) | Ratio of MW power to mass of wet coconut | Rehydration of moisture (g) | $k_1$ (min/g) | $k_2$ ($g^{-1}$) |
|---|---|---|---|---|---|---|
| 180 | 15 | 25.5 | 7 | 2 | 8.4634 | 1.8228 |
| 300 | 12 | 42.5 | 7 | 0.67 | 4.9954 | 1.6062 |

Other observations

- Rehydration was not significantly observable below the moisture ratio of 0.19 in both samples.
- The temperature rise within the coconut was significantly lower beyond the moisture ratio of 0.3 in both cases.

Based on the above results a suitable cycle can be designed by conveying coconut on a conveyor belt while supplying microwave sequentially for a portion of the belt and letting it cool for a portion of the belt. The belt speed can be adjusted according to the requirement of heating time and cooling time in an industrial scale continuous dryer.

# 5. CONCLUTIONS

- The main process variables, microwave power and initial mass loading, were found to have a significant influence on the drying time of the microwave assisted air drying of coconut kernel.

  The impact of microwave power was higher than the impact of mass loading on the total drying time. In fact, the influence of mass loading was found to be effective only above a critical value for a given microwave power. This could be generalized by finding the ratio of microwave power to mass loading (MPML) and the critical value of MPML was found to be around 3.7 $Wg^{-1}$ for the given experimental setup for microwave assisted air drying of coconut kernel. Statistical analysis showed that several thin layer models could be used to describe the drying behaviour of microwave assisted air drying of coconut kernel. The models such as Verma et al. model, Approximation of diffusion model, Midilli et al. model Logarithmic drying model and the Page model were found to show very good statistical compatibility with the experimental data. Therefore, the Page model with only two model constants was selected as the best model with $R^2$ being over 0.9842 and SSE (<0.0271) and RMSE (<0.0307) being considerably small values displaying a very good fit.
- The two model constants of the Page model were further analysed to find the correlations with the microwave power when the influence of mass loading is insignificant (i.e. MPML>3.7 $Wg^{-1}$). A new model is proposed as:

  $MR = exp( a. exp\left(\frac{M}{P}\right). t^{(c.P+0.6)})$ where, a= -0.07 $min^{-1}$, M=37.29 $Js^{-1}$ and c = 0.0007 $sJ^{-1}$. Parameter t (time) needs to be substituted in minutes and P in watts.

  The validation of the new model showed that the experimental results and the predicted results had a good fit with $R^2$ > 0.998 , reduced chi-square ($\varkappa^2$) < 0.00000322 and root mean square error (RMSE) <0.01771 in all cases indicating an excellent predictive model for microwave assisted air drying of coconut kernel.
- Effective diffusivity was found to be directly proportional to the microwave power at low mass loadings and hence the proportionality factor $D_{eff}/power$, was defined to describe the diffusivity of moisture during the microwave assisted air drying of coconut kernel. The value of this common factor for MPML greater than

3.7 $Wg^{-1}$ was found to be $1.3 \times 10^{-11}$ $m^2s^{-1}W^{-1}$ and it can be used to calculate the effective diffusivity when the supplied microwave power is known.

- An increased drying rate can be observed beyond the approximate moisture ratio of 0.35 in all microwave power levels. On an average initial moisture content of 85±5 % (w/w, dry basis), this moisture ratio corresponds to 30 % (w/w, dry basis) moisture content. This agrees with the previously reported value for the presence of free moisture up to about 30 % of the moisture content in the coconut kernel [7]. The second falling rate period is corresponding to the moisture content below 30 % (w/w, dry basis) and it is true for both hot air drying, and microwave assisted air drying of coconut kernel.
- A linearized shrinkage with moisture ratio was obtained as, $S = 0.5464MR + 0.4602$ for microwave assisted air drying of coconut kernel. This is comparable to the shrinkage behaviour of hot air drying of coconut kernel but the gradient of the linear variation was considerably low for hot air drying at 60 ºC. Further, the shrinkage behaviour of hot air drying of coconut compared with that of microwave drying of coconut revealed a change in drying pattern around the moisture ratio of 0.48.
- The quality of the VCO produced from coconut flakes dried using the method of microwave assisted air drying was within the standard industry parameters. The colour of the desiccated coconut had a slight variation in terms of yellow, 0.2 higher than the SLS 98 – 2018 on the Lovibond colour scale. This can be further optimised to fit within the ideal export guideline and a method comprising sequentially arranged microwave assisted air drying followed by air cooling is suggested for industrial practice.
- A case study analysis was presented for microwave powers of 180 W and 300 W including the heating and cooling times as well as the rehydration during cooling. Rehydration was not significantly observable below the moisture ratio of 0.19 and temperature rise within the coconut was significantly lower beyond the moisture ratio of 0.3.
- The comparative values of the gross analysis of energy consumption for hot air drying and microwave assisted air drying of coconut kernel were 8.8 kWh and 6.1 kWh respectively. However, the cost of production is a compromise between the energy consumption and the relative cost of the energy source.

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# Appendix A: External Lab Reports

COCONUT DEVELOPMENT AUTHORITY SRI LANKA

**පොල් සංවර්ධන අධිකාරිය**
**தெங்கு அபிவிருத்தி அதிகாரசபை**
**COCONUT DEVELOPMENT AUTHORITY**

ප්‍රධාන කාර්යාලය:
අංක 54, නාවල පාර, නාරාහේන්පිට, කොළඹ 05,
இல 54, நாவல வீதி, நாராஹென்பிட்டி, கொழும்பு 05.
No 54, Nawala Road, Narahenpita, Colombo 05.

මගේ අංකය / எனது இல. / My Ref No. } CDA/PD/2020/VS-014
ඔබේ අංකය / உமது இல. / Your Ref No. }
දිනය / திகதி / Date } 2020.01.22

## Certificate for Analysis of Virgin Coconut Oil

This is to certify that the **Virgin Coconut Oil** samples of below reference numbers handed over by **Mr.Fazlul Haq Muhammed Aadhil (University of Moratuwa), 25 1/1, Sri Mahabodhi Road,Dehiwala, Sri Lanka** on **2020.01.14** has been tested in the laboratory of Coconut Development Authority and the relevant test reports is attached herewith.

**Sample details**

| SCC identification number | Customer reference number | PD reference number |
|---|---|---|
| 9392 | 9392 | CO-20/007 |

M. D. Sbd
f Director -Processing Development

කොටුව කාර්යාලය.
අංක 11, ආදිපාද වීදිය, කොළඹ 01
இல 11, டியூக் பாதை, கொழும்பு 01.
No 11, Duke Street, Colombo 01.

Chairman : 94-11-2502501
Director General : 94-11-2508730
General Office : 94-11-2502502-4

Fax : 94-11-2508729
E-mail : chairmancdad@gmail.com
Web : www.cda.gov.lk
VAT No : 409046592-7000

# Coconut Development Authority

No. 54, Nawala Road, Colombo 05.

## TEST REPORT

**Customer :** Fazlul Haq Muhammed Aadhil – University of Sri lanka Moratuwa

**Sample No.: CO – 20/007**

**Sample Description:** Sample identified by the client as Virgin Coconut Oil
350ml of Oil sample submitted in a sealed Plastic bottle

**Date of sample received:** 16.01.2020 at 11.00 a.m.

**Sample submitted by:** Processing Development Division

**Date(s) of perfomance of test(s):**18.01.2020 to 20.01.2020

| No. | Parameter | Test method | Units | Results | Requirements of SLS 32:2017 (Virgin Coconut Oil) |
|---|---|---|---|---|---|
| **Physico Chemical** | | | | | |
| 01. | Colour (25 mm on the Lovibond colour scale) (Y+5R) | SLS-313-1-2009 | Lovibond colour scale | 0.4 | Not deeper than 1 |
| 02. | Moisture & other matter volatile at 105 $^{0}$C | MOC63U Moisture balance | % | 0.2 | 0.2 max |
| 03. | Free fatty acids ( as Lauric acid) | SLS-313-2-2009 | % by mass | 0.03 | 0.2 max |

**This report refers specifically to the test item(s) submitted.**
**This report shall not be reproduced except in total or in part, without written approval from the Director (QC & QA).**

Analyst:.....................

Authorized sig.:.....................

Date: 2020.01.21

W.M.M.P.D.K. Wijebandara
Assistant Director (QC & QA)
Coconut Development Authority
No. 54, Nawala Road,
Colombo - 05.

COCONUT DEVELOPMENT AUTHORITY SRI LANKA

පොල් සංවර්ධන අධිකාරිය

தெங்கு அபிவிருத்தி அதிகாரசபை

COCONUT DEVELOPMENT AUTHORITY


ප්‍රධාන කාර්යාලය:

අංක 54, නාවල පාර, නාරාහේන්පිට, කොළඹ 05,
இல 54, நாவல வீதி, நாராஹேன்பிட்ட, கொழும்பு 05.
No 54, Nawala Road, Narahenpita, Colombo 05.


මගේ අංකය / எனது இல. / My Ref No. } CDA/PD/2020/VS-015

ඔබේ අංකය / உமது இல. / Your Ref No. }

දිනය / திகதி / Date } 2020.01.22

## Certificate for Analysis of Desiccated Coconut

This is to certify that the **Desiccated Coconut** samples of below reference numbers handed over by **Mr.Fazlul Haq Muhammed Aadhill (University of Moratuwa), 25 1/1, Sri Mahabodhi Road, Dehiwala, Sri Lanka** on **2020.01.14** has been tested in the laboratory of Coconut Development Authority and the relevant test reports is attached herewith.

**Sample details**

| SCC identification number | Customer reference number | PD reference number |
|---|---|---|
| 9393 | 9393 | DC-20/001 |

M. D. Sbch

f Director -Processing Development


කොටුව කාර්යාලය.

අංක 11, ආදිපාද වීදිය, කොළඹ 01
இல 11, டியூக் பாதை, கொழும்பு 01.
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Chairman : 94-11-2502501
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General Office : 94-11-2502502-4

Fax : 94-11-2508729
E-mail : chairmancdad@gmail.com
Web : www.cda.gov.lk
VAT No : 409046592-7000

## Coconut Development Authority

No. 54, Nawala Road, Colombo 05.

### TEST REPORT

**Customer :** Fazlul Haq Muhammed Aadhil – University of Sri lanka Moratuwa

**Sample No.: DC-20/001**

**Sample Description:** Sample identified by the client as Desiccated Coconut
250g sample submitted in a sealed polythene bag

**Date of sample received:** 16.01.2020 at 11.00 a.m.

**Sample submitted by:** Processing Development Division

**Date(s) of perfomance of test(s):** 18.01.2020 to 20.01.2020

| No. | Parameter | Test method | Units | Result | Requirements of SLS 98:2013 Desiccated Coconut |
|---|---|---|---|---|---|
| **Physico Chemical Tests** | | | | | |
| 01. | Colour (25 mm on the Lovibond colour scale) | SLS-313-1-2009 | Lovibond colour scale | Y-1.1<br>B-0.1<br>R-0.2 | Y-0.9<br>B-0.1<br>R-0.2 |
| 02. | Moisture | MOC63U Moisture balance | % | 1.7 | 3.0(Max) |

**This report is provided based on the sample submitted.**
**Test report shall not be reproduced except in full, without written approval from the Director (QC & QA).**

Analyst:....................

Date: 2020.01.21

Authorized sig.:....................

W.M.M.P.D.K. Wijebandara
Assistant Director (QC & QA)
Coconut Development Authority
No. 54, Nawala Road,
Colombo - 05.