DRYING KINEICS OF COIR PITH AND THE PERFORMANCE IN FLASH DRYING

Jayakodi Arachchige Kumudu Malkanthi Fernando

118069P

Degree of Master of Philosophy

Department of Chemical and Process Engineering

University of Moratuwa

Sri Lanka

June 2016

DRYING KINEICS OF COIR PITH AND THE PERFORMANCE IN FLASH DRYING

Jayakodi Arachchige Kumudu Malkanthi Fernando

118069P

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Philosophy

Department of Chemical and Process Engineering

University of Moratuwa

Sri Lanka

June 2016

STATEMENT OF AUTHORSHIP

I do declare that this is my own work and this thesis does not incorporate any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning to the best of my knowledge without due acknowledgement and I do believe it does not contain any material previously published or written by me or any other person except where the acknowledgement is made in the text.

I do hereby grant permission to the University of Moratuwa, the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in further works (such as articles or books).

Signature:

Date:

J. A. K. M. Fernando (Candidate)

The above candidate has carried out research for the Masters/MPhil/PhD thesis/Dissertation under our supervision.

Signature:

Date:

Dr. A. D. U. S. Amarasinghe

(Principal Supervisor)

Signature:

Date:

Dr. (Mrs.) J. M. M. A. Jayasundera

(Associate Supervisor)

STATEMENT OF AUTHORSHIP

I do declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning to the best of my knowledge without due acknowledgement and I do believe it does not contain any material previously published or written by me or any other person except where the acknowledgement is made in the text.

I do hereby grant permission to the University of Moratuwa, the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in further works (such as articles or books).

Signature: Date:

J. A. K. M. Fernando (Candidate)

The above candidate has carried out research for the Masters/MPhil/PhD thesis/Dissertation under our supervision.

Signature: Signature:

Date: Date:

Dr. A. D. U. S. Amarasinghe (Principal Supervisor)

Dr. (Mrs.) J. M. M. A. Jayasundera (Associate Supervisor)

DEDICATION

Dedicated to my family members

ACKNOWLEDGEMENTS

First and foremost, I thank Almighty God for giving me strength, health, courage and perseverance for the successful completion of my M Phil. 1 wish to express my profound gratitude and appreciation to my supervisors Dr. A. D. U. S. Amarasinghe, Senior Lecturer, Department of Chemical and Process Engineering, University of Moratuwa and Dr. (Mrs.) J. M. M. A. Jayasundera, Former Head, Coconut Processing Research Division, Coconut Research Institute, Lunuwila. I appreciate very much Dr. A. D. U. S. Amarasinghe for his guidance and counselling in the area of material drying that provided me with the knowledge upon which this work was based. Thank you, dear supervisors for your prompt feedback and criticisms throughout the writing period. Without those I would not have been able to create this thesis.

I would like to express my sincere appreciation to Coconut Research Institute for the financial support and to the staff of Coconut Processing Research Division at Coconut Research Institute and the technical staff of the Pilot Plant Laboratory of the Department of Chemical and Process Engineering, University of Moratuwa for their assistance with lab experiments. My gratitude is extended to the staff of Dunkannawa Coir Research and Development Centre for their valuable co-operation during the period of study. I am grateful to Mrs. K. V. N. N. Jayalath, Research officer, Agriculture Economics Division, Coconut Research Institute for the support with the statistical analysis.

I wish to express my sincere gratitude to Mr. S. J. P. Samaratunge, owner of the Coco Green (Pvt) Ltd., for giving me the opportunity to manufacture coco discs and the staff for their assistance for making coco discs using the dried coir pith samples using different drying techniques during this research.

Finally, I would like to convey my heartiest thanks to my loving parents, sister and husband for their continuous support and encouragement, and a special thanks to my son and daughter for their patience and support which was a constant source of inspiration to carry out this work.

ABSTRACT

Drying and retting can be identified as the most important factors affecting the quality variations in dried coir pith which directly affects the final quality of compressed coir pith products. A pilot scale flash dryer was designed and fabricated to examine the effect of hot air temperature and velocity on the drying behavior of coir pith. Hot air drying was carried out to examine the drying kinetics by allowing the coir pith particles to fluidize and circulate inside the drying chamber. The physico-chemical properties of volume expansion ratio (VE), water retention capacity (WRC), bulk density, pH and electrical conductivity (EC) of compressed coir pith discs were measured. Scanning electron microscopy was used to analyze the microstructures of dried coir pith. The results were compared with the two other drying techniques namely sun drying and oven drying. The effect of time duration for retting and the method of retting the coconut husk were also examined.

The optimum temperature for coir pith drying was found to be 140 °C. The most suitable range of particle size and the range of moisture content in dried coir pith were identified as 0.5 – 6.3 mm and 12 - 23% (w/w, dry basis) respectively. The VE, WRC, pH and EC of coir pith dried in the flash dryer at the optimum temperature of 140 °C was found to be 5.01 ± 0.21, 4.02 ± 0.10 (w/w), 5.95 ± 0.08 and 330 ± 16 μs/cm respectively. These values were comparable with those of the sundried coir pith. Oven drying caused rupturing the cells and case hardening of coir pith. Similar effect was observed with temperatures > 140 °C for hot air drying and flash drying. VE and WRC of coco discs were found to increase significantly, pH to change marginally and EC to drop significantly with the increase of retting time.

The effective moisture diffusivity was found to increase from 1.18×10^{-8} to 1.37×10^{-8} m^2/s with the increase of hot air velocity from 1.4 to 2.5 m/s respectively. Correlation analysis and residual plots were used to determine the adequacy of existing mathematical models for describing the drying behavior of coir pith using hot air. A new mathematical model was proposed and it gave the best correlation between observed and predicted moisture ratio with high value of coefficient of determination (R^2) and lower values of root mean square error (RMSE), reduced chi-square ($\chi 2$) and mean relative deviation (E %). Wang and Singh model and Linear model were also found to be adequate for accurate prediction of drying behavior of coir pith. Since the experimental setup of this study closely simulated the particle motion and heat and mass transfer in flash drying due to induced fluidization and circulation, the new model has a great potential in designing and modeling of the flash drying of coir pith.

Key words: Coconut coir pith, Retting, flash drying, drying models, effective moisture diffusivity

TABLE OF CONTENTS

CHAPTER FOUR

CHAPTER FIVE

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviations	Description	
a ,b, c, k, n	Constants in drying model	
a_2, b_2, c_2	Constants in drying model	
a_3, b_3, c_3	Constants in drying model	
BD	Bulk density of coir pith	(g/l)
BL	Breaking load	(N)
C	Calorific value of the kerosene	(kJ/l)
C/N	Carbon/Nitrogen	
CR	Compression ratio	
D_{eff}	Effective moisture diffusivity	(m^2/s)
DR	Instantaneous drying rate	(g water /g dry matter Per min)
E %	Percent mean relative deviation	
EC	Electrical conductivity	(μs/cm)
HAD	Hot air drying	
M	Moisture content at any time	(kg water/kg dry matter)
M_e	Equilibrium moisture content	(kg water/kg dry matter)
M_o	Initial moisture content	(kg water/kg dry matter)
MR	Moisture ratio	(kg water/kg dry matter)
$MR_{exp,i}$	i^{th} experimental moisture ratio	(kg water/kg dry matter)
$MR_{pre,i}$	i^{th} predicted moisture ratio	(kg water/kg dry matter)
M_t	Moisture content at time t	(kg water/kg dry matter)
M_{t+dt}	Moisture content at time t+dt	(kg water/kg dry matter)
n	Number of constants in the model	
N	Number of observations	
OD	Oven drying	
P	Particle size	(mm)
P_{bl}	Amount of energy consumed by the blower	(J)
r	Radius of sphere	(m)
R^2	Coefficient of determination	

RMSE	Root mean square error	
SD	Sun drying	
SEM	Scanning electron microscopy	
SMER	Specific moisture extraction rate	(kg/kWh)
t	Time	(min)
TS	Tensile Strength	(N/mm^2)
VE	Volume expansion ratio	
W	Amount of kerosene used by the blower	(L)
WRC	Water retention capacity	(kg water/kg dry solid)
χ^2	Reduced chi-square	

LIST OF APPENDICES

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Compressed or compacted coir pith products are innovative and lucrative growth medium, vastly used in agricultural and horticultural industries in all over the world. Coir pith is a light spongy and lignocellulosic material liberated out during the extraction of golden coir fibre from the husks of coconuts (Kadalli and Nair, 2000; Jayaseeli and Raj, 2010). Coir pith is abundantly available in major coconut producing countries such as Philippines, Indonesia, India, Sri Lanka and Malaysia (Sri Lanka Coconut Statistics, 2012). Usage of coir pith is becoming popular in the world due to its characteristics such as high water retention capacity due to the porosity of the cell structure and the fertility as it contains micro and macro nutrients mainly K^+ ions (Raquepo, 2004). Hence it is mostly used as a growth medium especially for hydroponics (Krisnamurthy et al., 2009). Currently coir pith has a growing demand since it is a sound alternative to sphagnum peat which is widely used as a standard growth medium all over the world (Konduru et al., 1999). Coir pith has been identified as an excellent growing medium for ornamental crops such as ixora, majesty palm, anthurium and ericaceous plants (Meerow, 1994; Scagel, 2003).

Method of extraction, area of cultivation and aging have been found to influence the composition, particle size distribution and the physicochemical properties of coir pith (Moorthy and Rao, 1998; Tharanga et al., 2005). The increase in particle size leads to decrease in the porosity, density, absorptivity and electrical conductivity whilst increasing the pH of raw coir pith (Ross et al., 2012). Particle size distribution of coir pith may also be influenced by the method of pre-processing of coconut husks namely, crushing, soaking, water spraying and retting. The physicochemical properties such as pH, electrical conductivity, C/N ratio and cation exchange capacity of coir pith samples were found to be significantly different between and within those of the samples obtained from different countries and were significantly different from those of sphagnum peat (Abad et al., 2002; Evens et al., 1996;

Konduru et al., 1999). Similarly retting may also affect the physicochemical properties of coir pith and the present study examines the influence of the method of retting and the retting time on the physicochemical properties and the particle size distribution of coir pith.

Drying of coir pith is essential for the manufacture of compressed coir pith products and it plays a major role on quality of the final products. Reduction of moisture to a desired level is highly essential for conserving the quality of coir pith mainly water retention capacity and volume expansion, in order to apply it as a growth medium in agricultural and horticultural industries (Abad et al., 2002; Sarma, 2008). Sun drying under natural convection is economical and it is the conventional method of drying coir pith. It is a low cost heating source (Domaz and Ismail, 2011) but having some inherent disadvantages (Kooli et al., 2007). Slowness of the process, weather uncertainties especially long rainy seasons, high cost of man power, large area requirement, insect infestation and contaminating with foreign materials are prominent draw backs of sun drying. Sri Lanka is a tropical country and uses sun drying heavily for reduction of moisture in agricultural materials such as coir pith. At present, coir industry is not in a position to meet the current demand due to the problems associated with sun drying and hence finding of alternative drying techniques is a timely need for sustaining the coir pith industry. In this research drying characteristics and quality variations of coir pith due to the method of drying were investigated for sun drying, oven drying and hot air drying.

Hot air is used in many industrial drying applications due to several advantages including fast and uniform drying (Mosquera et al., 1994; Ayensu, 1997). Some of the coir pith manufacturers in Sri Lanka also use hot air dryers, especially flash dryers, for drying of coir pith. However, they are unable to achieve the required quality, specifically volume expansion due to poor controlling of processing parameters. Most of the flash dryers use flue gas as the drying medium and hence coir pith is exposed to extremely high temperatures (above 200 °C) for longer periods. This may be mainly attributed to the lack of reliable information on suitable drying temperature and drying kinetics of coir pith during hot air drying. In the present study the kinetics of coir pith drying was examined for hot air drying with fluidization and circulation.

Mathematical modeling for hot air drying of coir pith was also performed in this study as simulation of drying curve which directs better control of drying process to obtain high quality product (Meisami-asl et al., 2009). It can be further used to study the drying variables, evaluate the drying kinetics and to optimize the drying parameters and conditions (Karathanos and Belessiotis, 1999).

Introducing a reliable and highly efficient drying technique is needed for the coir pith industry to produce good quality products based on coir pith. Flash dryers are currently used by several manufacturers but they find it difficult to control the process due to the lack of information on drying kinetics and product quality. Present study examines the performance of flash drying technique with reference to the product quality, cycle time and the operating temperature.

1.2 Objectives of the Project

- To examine the effect of time duration of retting and method of retting of coconut husks and method of drying of coir pith on quality of coir pith and coco discs.

- To examine the drying kinetics and mathematical modeling of hot air drying of coir pith with fluidization and circulation.

- To establish the factors affecting the flash drying of coir pith and to analyze the performance of a proposed flash drying system.

1.3 Outline of the Thesis

This thesis consists of ten chapters as follows

Chapter 1: Introduction presents the importance of coir pith and its current usage as a growth medium in horticultural and agricultural industries in brief. It describes the influence of processing steps of coir pith such as pre-processing methods before extracting fibre from coconut husks and drying of coir pith, on its quality. A brief description on the importance of studying the drying mechanisms of coir pith and the mathematical modeling associated with drying is also given. Finally, the objectives of this study are given.

Chapter 2: Literature review is organized to give a perspective on coir fibre manufacturing in Sri Lanka, potential of coir pith, previous studies related to coir pith, comparison of different drying techniques and the importance of the mathematical modeling for material drying. Finally, justification of this study is stated.

Chapter 3: It describes the concepts, theory and equations used for analyzing the data with respect to the physicochemical and mechanical properties of coir pith, mathematical modeling, drying characteristics and statistical methods.

Chapter 4: It describes the materials and methods adopted in this study including different modes of retting, investigation of different drying techniques namely, sun drying, oven drying, hot air drying, flash drying and also the establishment of a suitable mathematical model for coir pith drying.

Chapter 5: It describes the results of preliminary studies on the assessment of the suitable range of particle sizes, suitable moisture content and the optimum drying temperature of coir pith to achieve good quality coir pith and hence to manufacture good quality coir pith products.

Chapter 6: It examines the effect of time duration of retting of coconut husks on quality variation of coir pith and coir fibre. It also examines the effect of pre-processing methods employed for different extraction methods on particle size distribution and the quality variations in sun dried coir pith. The reduction of microbial content due to sun drying of coir pith obtained from different extraction methods is also discussed.

Chapter 7: Quality variation of coir pith under three different drying techniques; sun, oven and hot air drying, is described here. Moreover, the effect of these drying methods on the reduction of microbial content and microstructural changes in coir pith is also discussed.

Chapter 8: It concentrates on studying the drying characteristics for hot air drying of coir pith. A new mathematical model has been introduced for describing the drying of coir pith using hot air. Effect of velocity on moisture diffusivity is also discussed.

Chapter 9: It presents the results of experimental investigation of coir pith drying in a pilot scale flash dryer fabricated at the Coconut Research Institute (CRI), Sri Lanka. The statistical analysis of the quality parameters for the determination of optimum drying temperature is given. The effect of important process variables such as temperature and air velocity is also examined. Finally, the quality of products from flash drying technique is compared with the quality of sun dried products. The effect of drying temperature on structural changes of coir pith is also discussed in this chapter.

Chapter 10: It gives the conclusions and the recommendations made in the study at each phase and suggestions mainly for improving flash drying technique for the coir pith drying.

CHAPTER TWO

2.0 LITRATURE REVIEW

2.1 Overview of the Coir Fibre Manufacturing in Sri Lanka

2.1.1 Coir industry in Sri Lanka

Coconut is the 3rd main crop in Sri Lanka and Sri Lanka is the world fourth largest producer of coconut contributing to an average of 2500-2800 million nuts per year where the global production is about 73811 million nuts per year (Sri Lanka Coconut Statistics, 2014). However only 10% husks of the global production of coconuts are utilized in the coir industry and coir industry has been developed only in a handful of coconut producing countries such as Sri Lanka, India, Philippines, Thailand and Malaysia. Sri Lanka and India are the main coir fibre suppliers to the world market which accounts for about 90% of the world market share. However, Sir Lanka is the single and the largest supplier of bristle fibre (brown) to the world market. The fibre extraction machine named Ceylon Drum system in Sri Lanka is capable of producing such a high quality product which is a unique raw material for the production of "thawashi" brushes, door mats, carpets, ropes, etc. Moreover, it has provided about 40000 job opportunities.

Coir products mainly exported from Sri Lanka and India are in the form of mats, mattings, rugs, carpets, needle felt, rubberized coir, geo-textiles, etc. Currently usage of them is becoming popular because they lead natural, eco-friendly and bio-degradable products.

2.1.2 Fibre extraction methods

D1 method and Ceylon Drum method are employed for fibre extraction in Sri Lanka. In D1 method husks are half broken by spikes, fitted to a rotating drum. The half broken husks are then transferred to a turbo cleaner in order to defibre by means of beaters, fitted to the main shaft of turbo cleaner. The machine is capable of producing mixed fibre using green husks and retted husks or wetted husks. In Ceylon Drum method breaking and cleaning of retted husks are done by means of spikes, fitted to two rotating drums called breaker drum and cleaner drum. Retting of coconut husks is highly essential before the extraction of coir fibre from coconut husks by this method.

2.1.3 Retting

Retting is the method of soaking coconut husks in water. It is the process of degradation and decomposing of pectin and poly-phenolic compounds associated with coir fibre by a microbial process to remove coir fibre from the coconut husks. It is a natural process and facilitates the easy extraction of coir fibre (Ravindranath, 2001). The degree of retting of coconut husks affects the quality of coir pith which is a by-product of coir industry. Retting of husks is highly important for the production of high quality bristle fibre for which Sri Lanka is the single and major supplier to the world market.

2.1.4 Importance of coir pith and compressed coir pith products

Natures wonder coir fibre is extracted from the mesocarp of the coconuts (*Cocos nucifera* L). During this extraction a light spongy ligno-cellulosic material gets released. This spongy material is referred to as coir pith (Jayaseeli and Raj, 2010). Bhat and Nambudier (1972) stated that coir fibre was bound with each other by non-fibrous tissues named as coir pith. These tissues are formed by parenchymatous cells. Narendar and Priya (2012) reported that coir pith contains 30-35% of lignin, 20-25% of cellulose, 1.8% of fats and resin, 7.45% of pentosans, 8.7% of ash and 3.23% of nutrients. Coconut husks comprise of 35% of total weight while the kernel (copra, coco water and shell) contributes to 65 %. These coconut husks contain 70% of pith and the rest is coir fibre. As a result, coir fibre extraction process generates large quantities of pith which accumulates at the production site over the years. Approximately for the extraction of each kg of fibre, more than 2 kg of coir pith (dry basis) is generated. Therefore, in the past coir industries faced great difficulty in the disposal of coir pith (Dan, 1993). Very often coir pith was heaped as mound on the way sides (Figure 2.1).

Large quantities of coir pith thus stored cause contamination of ground water due to the percolation of leachates containing residual phenol from these dumps. To overcome the problems associated with coir pith, innovative practices are being followed. At present there is an increasing demand for coir pith as an alternative to sphagnum peat.

Figure 2.1: Typical coir pith mound in Nattandiya area in Sri Lanka

Sphagnum peat is widely used in the U.S, Europe and Canada (Dan, 1993) as a potting medium mainly for containerized crops and transplant of most agricultural and horticultural applications, rather than other growth media such as municipal and agricultural wastes, paper sludge, coal ash, shredded rubber and cotton waste. However, due to the high cost of sphagnum peat and the uncertainty of availability in the future as a result of high usage, it is important to find a suitable substrate as an alternative to peat. Coconut coir dust has already been identified as an alternative to peat (Evens et al., 1996) due to its inherent quality characteristics. As a result of the porous nature in coir pith cells, it has an excellent compressibility in packaging without disturbing the original structure. Coir pith has a great demand in all over the world as it has immense potential as a soil conditioner that improves water retention in natural way. It has high lignin to cellulose ratio and hence it remains in the soil for longer time compared to peat. Coir pith also increases the organic matter content in the soil. Therefore, it is applied prominently in horticulture as a surface mulch/rooting and also used as a desiccant and removal of heavy metal particles. Coir pith absorbs liquids and gases (odours). This property is resulted by honey comb like structure of the mesocarp tissue which gives high surface area per unit volume where moisture spreads readily over these surfaces due to inherent quality of hydrophilic nature. It improves the absorption of air and other gases. Coir pith also has a potential for making bricks, bio filter and manufacture of particle boards. Figure 2.2 illustrates some applications of coir pith.

Figure 2.2: Applications of coir pith

2.2. Analysis of the Quality Variations in Coir pith

2.2.1 Physicochemical properties of coir pith

The quality of coir pith depends on the mode of extraction, mode of pre-processing of coconut husks, mode of drying, etc. In Sri Lanka conventional fibre extraction system named Ceylon Drum method is used for the extraction of coir fibre from retted husks which have been subjected to more than 3 months of retting. D1 method is widely used for the extraction of fibre from non-retted husks by direct decortication after soaking dry husks for less than one week or water spraying on fresh husks for two or three days. Table 2.1 and Table 2.2 show physical properties of raw coir pith and the chemical composition and chemical properties of retted and non-retted coir pith. Retted coir pith has lower lignin content compared to that of non-retted husks.

Table 2.1: Physical properties of raw coir pith

Properties	Value
Bulk Density (g/cm^3)	0.15
Particle Density (g/cm^3)	0.49
Porosity (%)	76.77
Maximum water holding capacity (%)	624.77
Volume expansion (%)	22.92

Source: Manufacture of coir and coir based products, 1997

2.2.2 Factors affecting the quality variations in coir pith

Several investigations were carried out in the determination of factors affecting the quality of coir pith products. Tharanga et al. (2005) studied the variation of chemical and physical properties of raw coir dust. These Properties were determined in coir pith samples collected from 4 main coconut cultivating districts in Sri Lanka. They found that extraction methods of coir fibre influenced the particle size distribution of coir pith and also affected the physical parameters but not the expansion property of coir pith. Areas of origin as well as aging were identified as the other factors affecting the variation of properties like salinity (EC) of coir pith.

The effect of particle sizes on physicochemical properties of coir pith was determined by Ross et al. (2012). They investigated properties such as porosity, density and absorptivity of coir pith with the average particles sizes in the range from 300μm to 2000μm obtained from Kullanchavadi village, Cuddalore District, Tamil Nadu. They observed that increase in particle size led to decrease in the porosity, density and absorptivity whilst increase in pH of raw coir pith. The electrical conductivity was observed to be gradually decreasing with increasing particle size.

Table 2.2: Chemical composition and chemical properties of coir pith

Constituents	Non-retted coir pith	Retted coir pith
Lignin (%)	38.50	30.00
Cellulose (%)	26.40	25.10
Organic Carbon (%)	29.50	29.00
Nitrogen (%)	0.24	0.26
Phosphorous (%)	0.01	0.01
Potassium (%)	0.71	0.76
C: N ratio	123:1	112:1
Calcium (%)	0.40	0.47
Magnesium (%)	0.36	0.41
Copper (ppm)	3.10	4.20
Iron (ppm)	0.07	0.08
Manganese (ppm)	12.50	17.00
Zinc (ppm)	7.50	9.80
pH	5.4 - 5.8	5.6 - 6

Source: Radhakrishnan et al., 2012

Abad et al. (2002) evaluated the physicochemical and chemical characteristics of coir dust as peat alternatives. They investigated the physicochemical properties of 13 coir pith samples collected from Asia, America and Africa. These properties were compared with those of Sphagnum peat. They revealed that properties such as pH, electrical conductivity, C/N ratio and cation exchange capacity were significantly different between and within the samples obtained from above mentioned countries and were significantly different from sphagnum peat.

Evens et al. (1996) investigated the physicochemical properties of coir pith obtained from 12 different locations in Philippines, Indonesia and Sri Lanka. They found that physical properties such as bulk densities, air filled pore space, water filled pore space and total pore space were significantly different in coir pith samples obtained from five different locations in Philippines. Bulk densities were found to vary in between 0.04 and 0.08gcm^{-3}. They revealed that chemical properties such as pH and EC (ranged from 5.6 to 6.9 and 0.3 to 2.9 ms/cm) were significantly different from among coir pith samples. There were no significant differences with respect to Fe, Mn, Zn, B, Cu, NH_4-N and Mg concentrations. However, there is only limited literature available on the effect of pre-processing methods on quality of coir pith.

2.3 Market Potential

Sri Lanka is considered as a major coir exporting country in the world only second to India. Coir pith is an important constituent of coir exports, earning more than 15% of the total export earnings of coconut products (Sri Lanka Coconut Statistics, 2014). The main products based on coir pith include bales, briquettes, discs and grow bags. Export of compressed value added products rather than in the bulk form is a potential foreign exchange earner to Sri Lanka. Table 2.3 shows the export earnings from 2010 to 2014 and Table 2.4 shows the major coir pith importers of Sri Lanka.

Table 2.3: Export earnings of coir pith products

Year	2010	2011	2012	2013	2014
Volume(MT)	174,308	196,460	199,645	143,911	157,177
Earning (US$. Mln)	53.7	65.9	67.8	74.6	82.1
Earnings from coconut products	286.9	427.8	365.6	371.5	558.2

Source: Sri Lanka Coconut Statistics, 2010-2014

Table 2.4: Major countries importing coir pith from Sri Lanka

Country	Export Volume (MT)- 2013
Japan	38,157
South Korea	18,409
China	12,774
Spain	7,981
Italy	6,158

Source: Sri Lanka Coconut Statistics, 2013

Table 2.3 indicates that foreign exchange earnings from coir pith have increased with time. Nevertheless Tharanga et al. (2005) reported that competition was arising from other countries in Asia, America and Africa for exporting this horticultural substrate. Table 2.4 shows that there is a high demand for Sri Lankan coir pith products in the world specially Japan, South Korea and China.

2.4 Process of Drying

Drying is one of the major factors affecting the quality of coir pith products. Drying can be defined as a dual process of heat and mass transfer resulting in the removal of moisture to a certain level by evaporating from the materials to the surrounding air (Ekechukwu and Norton, 1999; Ozdemir and Devres, 1999). In this process, removal of moisture mainly happens by diffusion from inside to the outer surface of a material (Menges and Ertekin, 2006). It performs a significant role mainly in the preservation of biological materials such as fruits, vegetables and agricultural products so as microbial activity and deterioration due to chemical reaction are considerably minimized (Prakash et al., 2004). Presence of water in material like food, may activate enzymes and cause for spoilage (Misha et al, 2013). When drying occurs, structural and physicochemical modifications can also be occurred and may result in lowering the degree of its quality (Wankhade et al., 2012). The process of drying causes substantial reduction in volume, weight, minimizing packaging, storage and transportation costs. It also enables the ability to store the product under ambient temperature (Akpinar et al., 2006).

2.4.1 Free and bound water

In coir pith water can be found in the cell cavities and cell walls. All void spaces in coir pith can be filled with liquid water which is free water. Free water is held by adhesion and surface tension forces. Water in the cell walls is the bound water. Bound water is held by forces at molecular level. Water molecules attach themselves to sites on the cellulose chain molecules. It is an intimate part of the cell wall but does not alter the chemical properties of coir pith. Hydrogen bonding is the pre-dominant fixing mechanism. If coir pith is allowed to dry, the first water to be removed is the free water. No bound water is evaporated until all free water has been removed. During removal of water, molecular energy is expended. Energy requirement for vaporization of bound water is higher than that of free water.

2.4.2 Equilibrium moisture content

In the process of drying, removal of bound and unbound moisture occurs in a material. The moisture removal in the form of unbound water takes place under the two methods; evaporation and vaporization. Evaporation occurs when the vapour pressure of the moisture on the solid surface is equal to the atmospheric pressure. This is done by raising the temperature of the moisture to the boiling point. At the end of drying the vapour pressure of the solid becomes equal to the partial vapour pressure of the drying air and no further evaporation takes place. The limiting moisture content at this stage to which a material can be dried under the given drying condition is referred to as the equilibrium moisture content (M_e).

2.4.3 Moisture removal

Normally water moves as a result of concentration gradient of moisture content. The surface of the material must be dried more than the interior if moisture is to be removed. Drying can be divided into two phases: moister transfer from the interior to the surface of the material and evaporation of moisture from the surface. Water moves from the material through the interior of the air passage ways of the cellular structure and through the cell walls. Water removal occurs under the main mechanisms: capillary action (liquid) and diffusion of bound water (vapour). Capillary action causes free water to flow through the cell cavities and pits. Diffusion causes the movement of bound water due to the concentration gradient of moisture content and the relative humidity. Material gets dried via the simultaneous process of heat and moisture transfer.

2.5 Methods of Drying

Several drying methods are employed for the removal of moisture in different agricultural products. Those methods have their own advantages and limitations. For the selection of right drying system, it is essential to study the available system and compare with traditional drying methods for the reduction of drying time and to achieve significant improvement to the product quality.

2.5.1 Open sun drying

Open sun drying has been used mainly in tropical countries since ancient time to dry different materials including agricultural products. It involves direct radiation and hence the products get dried. Sun drying is a cost effective heating source and widely used for drying of various vegetables, fruits and agricultural products such as cut vegetables (Jaros and Pabis, 2006), oil palm trunk waste (Nadhari et al., 2014), finger millets (Radhika et al, 2011), mint, parsley and basil (Akpinar, 2006) and grape leather (pestil)(Maskan et al., 2002). Sun drying can be identified as the main technique for drying of coir pith mainly for the cost effectiveness (Domaz and Ismail, 2011), no expertise is required and also yields good quality coir pith. However, sun drying has the drawbacks such as longer period of drying, uncertainty in weather condition mainly long rainy seasons, excessive labour, large area requirement, insect infestation and addition of other foreign materials. Arslan and Ozcan (2010) studied the effect of sun, oven and microwave drying of onion slices on its quality. Sun and microwave dried onion gave better colour values while oven dried samples gave high mineral values.

2.5.2 Fluidized bed drying

Fluidized bed drying can be expressed as a highly efficient drying technique as it involves uniform and high heat transfer rate over the materials (Sutar and Sahoo, 2011) and gives good quality products. Prakash et al. (2004) investigated the performance of blanched carrot dried in solar cabinet dryer, fluidized bed dryer and microwave dryer. They found that drying happened mainly in the falling rate period and also the better quality of carrot was gained by fluidized bed drying than that was given by solar cabinet dryer and microwave oven. Tasirin et al. (2007) investigated the performance of fluidized bed drying of bird's eye chilies. The drying experiments were performed at temperatures of 50, 60 and 70 °C and at velocities of 0.85, 0.97 and 1.09 m/s. They also used the method of direct sun drying. The dried chilies were tested for quality conservation in terms of colour aroma and taste. The quality of fluidized bed dried chilies was found to be better compared to those undergone sun drying.

2.5.3 Hot air drying

In this method heated air is bought into contact with the wet material to be dried to facilitate heat and mass transfer where convection is mainly involved. Two important aspects of mass transfer are the transfer of water to the surface of material that is dried and the removal of water vapour from the surface.

The hot air dryers which are generally used for the drying of agricultural products such as fruit and vegetables are cabinet, kiln, tunnel, belt–trough, bin, pneumatic and conveyor dryers. Energy source to heat the air would be electricity or a renewable energy resource such as solar and geothermal energy. In solar dryers, solar radiation is consumed by air and heated air is ducted to the drying chamber.

2.5.4 Flash drying

A flash dryer is a pneumatic system which can be characterized as continuous convective dryer in which the drying energy and transport of the solids throughout the vertical pipe is supplied by hot air (Baeyens et al., 1995). In flash drying, solid particles are well mixed with high velocity hot air stream resulting in very rapid drying. It is widely used in industrial applications as a result of involving high rate of moisture evaporation due to high temperature, sudden pressure reduction, and exposure of high surface area for heat and mass transfer (Skuratovsky et al., 2005; Aslaksen, 2014). It is not a complex system and hence low investment is needed for the construction (El-Behery et al., 2011). This drying technique is very appropriate for drying of granular or free flowing solids successfully.

Several studies were performed to investigate the performance of the flash dryer by dehydration of materials such as wheat grains (Matsumoto and Pei, 1984), rice powder (Tanaka et al., 2008), coal (Aslaksen, 2014) etc. Pneumatic drying of saw dust was performed by Bhattarai et al. (2012) and they developed a simulation model for saw dust drying. Recently, Ajao and Adegun (2009) achieved moisture content of 57.1% in cassava mash using a mini flash dryer with 3 passes.

2.6 Mathematical Modeling of Drying

Mathematical modeling and simulation of drying curve is useful for better control of drying and to obtain high quality product (Meisami-asl et al., 2009). It can be further used to study the drying variables, evaluate the drying kinetics and to optimize the drying parameters and the conditions (Karathanos and Belessiotis, 1999). Yun et al. (2013) reported that mathematical modeling was successful in designing of improved drying system. Thin layer drying models are widely used to establish the mathematical models for drying of agricultural products. The principal of modeling is based on having a set of mathematical equations which can satisfactorily describe the drying system (Garavand et al., 2011). Those can be grouped as theoretical and semi-theoretical models derived from Fick’s second law and empirical models regarding the liquid diffusion. Lewis, Page, Henderson and Pabis, Logarithmic, two term and Verma et al are the most widely used theoretical models while Thompson and Wang and Singh models, can be named as empirical models. Kaushal and Sharma (2014) reported that empirical models well describe both removal of water at thin layer material and heat transfer during the removal of water.

Mathematical modeling was performed for many agricultural products and porous materials such as bird’s eye chilies (Limpaiboon, 2015), Alfalfa (Farhang et al., 2010), unripe plantain chips (Famurewa and Adejumo, 2015) and bay leaves (Demir et al., 2004). Kakade and Hathan (2014) investigated the drying characteristics and the rehydration ratio of beetroot leaves samples under the effect of blanching. The drying data were fitted with existing thin layer drying models and found that the drying kinetics were well described by Wang and Singh model. Blanched beetroot leaves samples resulted in lower rehydration ratio and lower drying time compared to those of unblanched samples due to the effect of rupturing of cells. Wang and Singh model was also found to satisfy the drying kinetics of thin layer mango pulp added with egg white in different percentages as foaming agent. Mango pulp consisting of 3% egg white and the drying temperature of 65°C showed the highest carotene content (Wilson et al., 2012). The dehydration kinetics of osmotically pre-treated jackfruit samples using 15% salt solution was investigated at the temperatures of 50, 60 and 70°C by Kaushal and Sharma (2014) and the drying data were fitted to the thin layer mathematical models. They compared R^2, RMSE, $\chi 2$ and percent mean relative deviation (E %). Wang and Singh model was found to be the best model for describing the drying behavior of pretreated jack fruit samples.

Drying characteristic of another agricultural product namely orthodox broken type tea was examined by Raveendran et al. (2013). Drying experiment was conducted in a fluidized bed dryer at the loading rate of 29 kg/m^2 and a range of temperatures in between 108 and 127°C. Tea was dried from the moisture content of 106% (w/w, dry basis) until it reached 7% (w/w, dry basis). Page model was found to be the best for describing the drying kinetics of orthodox broken type tea.

Ozcan et al. (2005) studied the effect of sun and oven drying on mineral content of basil herbs. The drying experiment was carried out under open sun and in oven drying at 50°C. Drying characteristics was also determined for these two drying modes. They found that oven dried herbs had higher mineral content compared to sun dried herbs. Further they found that drying was satisfactorily described by Lewis model and correlation coefficient for herbs was higher under sun drying than that of oven drying.

Akpinar (2006) investigated the mathematical modeling for drying of parsley, mint and basil under direct sun drying. Experimental data were fitted to twelve different mathematical models described in literature. Performance of these models was determined by comparing the values of R^2, RMSE and χ^2. The drying characteristics of mint and basil leaves was well described by Modified Page(I) model while that of parsley leaves was well described by Verma et al. model.

Drying characteristics of paddy were studied in an integrated dryer consisting of solar, bio mass and electrical sources by Manikantan et al. in 2014. The paddy was dried to reduce the moisture content from 22 to 13 % (w/w, wet basis). The drying time was limited to 5 - 9 hrs. Time variation was dependent on the energy source used. The drying data were fitted to six thin layer drying models and the performance of these models was investigated. Wang and Singh model was found to be the best for describing the drying behaviour of paddy using solar, bio mass and combined heating sources. However, Page model was found to be the best for electrical heating source.

Drying is an essential step in processing of coir pith. However improper drying leads to negative effects on the structure of biological material such as loss of dehydration ability, case hardening, colour changes, shrinkage of cells etc.

2.7 Justification

Quality is the major requirement in the exports of compressed coir pith products. Although Sri Lanka is a major coir exporting country in the world only second to India, currently coir pith industry in Sri Lanka faces several quality associated problems including the variations in physicochemical properties due to lack of proper knowledge in pre-processing methods, microbial contaminations of coir pith and drying aspects. Pre-processing methods of coir pith may influence the quality of final products. Crushing, retting, soaking and water spraying of coconut husks can be considered as the widely used pre-processing methods in fibre extraction by employing D1 method and Ceylon Drum method. When coconut husks are crushed, the bonds in between fibre strands and the coir pith get loosened and hence it leads to an increase in the water absorption. Although several studies were carried out in the past with respect to the growth medium for foliage, hydroponics, fruits and vegetables and purification of substances like iron ores from the contaminations like heavy metallic particles and effectiveness of usage of coir pith as composting material, effect of particle sizes on quality of coir pith, there were only a limited number of studies carried out with respect to the effect of pre-processing methods on particle size distribution of coir pith. Particle size distribution of coir pith plays a major role in the quality aspects in the application of coir pith as potting medium in export market.

Drying of coir pith is an essential factor for producing coir pith in compressed forms. The mode of drying of coir pith may alter its quality. Natural sun drying is the most commonly used drying practice in the coir industry. However, it lags the rate of production especially in rainy seasons affecting the export demand. Although hot air drying technique is used by some people to address this issue, high quality coir pith could not be achieved so far due to use of high temperatures beyond 200^{o}C and also due to uncontrollable drying associated with flue gas as the drying medium. Studying of efficient drying techniques and evaluation of their performance are timely needs to achieve high quality standards in coir pith for the sustainability of coir industry in Sri Lanka. Mathematical modeling of coir pith is also important to understand the process and to control and optimize the process which affect the quality constrains and capital cost.

.

CHAPTER THREE

3.0 DATA ANALYSIS

3.1 Analysis of Physical Properties of Coir Pith

3.1.1 Moisture content

Moisture content of coir pith samples were analyzed using standard oven method according to Sri Lanka standards (SLSI, 2001). The following equations were used to calculate the initial moisture content, instantaneous moisture content and the moisture ratio.

A) Initial moisture content

$$M_o = \left(\frac{W_0 - W_f}{W_f}\right) \times 100 \qquad [3.1]$$

B) Instantaneous moisture content

$$M_t = \left(\frac{W_t - W_f}{W_f}\right) \times 100 \qquad [3.2]$$

C) Moisture ratio

$$MR = \frac{M_t - M_e}{M_o - M_e} \qquad [3.3]$$

Where

M_o = Initial moisture content (kg water/kg dry matter),

M_t = Moisture content at time *t* (kg water/kg dry matter)

M_e = Equilibrium moisture content (kg water/kg dry matter)

W_0 = Initial weight of the sample

W_f = Final weight of the sample

W_t = Weight of the sample at time t

3.1.2 Particle size distribution

Dry coir pith having moisture content of 16 - 17 % (w/w, dry basis) was first sieved using a net of mesh size ¼ inch to remove the large particles. Three samples of 500 ± 2 g were randomly selected to analyze the particle size distribution using sieves of mesh sizes 0.5, 1.0, 2.0, 2.8 and 4.0 mm. The average weight of coir pith for each mesh size was then obtained using electronic balance (Shimadzu, BX–K/BW-K, Japan). Sieved coir pith was categorized into three main types as coarse, medium and fine in accordance with greater than 2.8 mm, between 1.0 and 2.0 mm and less than 1.0 mm, respectively.

3.1.3 Bulk density

Coir pith samples having moisture content of 16 - 17% (w/w, dry basis) were used to measure the bulk density. They were filled into a cylinder of 1000 ml and a weight of 650 g was applied on the top (SLSI, 2001). Bulk density of coir pith (BD) was calculated as the ratio of weight to volume of coir pith in the cylinder.

3.1.4 Microbial content of coir pith

Microbial content of coir pith samples were analyzed for common bacterial species (pour plate method). Identification of *E-coli* and *salmonella* was performed according to the Sri Lanka Standards (SLSI, 1991).

3.2 Analysis of Physicochemical Properties of Coco Discs

Coco discs were prepared using dried coir pith samples having moisture content of 16 - 17% (w/w, dry basis) by compressing under 1500 psi. The specifications of coco discs were height of 24 ± 1 mm, diameter of 78 ± 1 mm and weight of 60 ± 2 g. They were analyzed according to Sri Lanka standards (SLSI, 2001) for the physical properties of volume expansion ratio (VE), water retention capacity (WRC) and also for the chemical properties of pH and electrical conductivity as mentioned in the section 3.2.1 and 3.2.2, respectively.

3.2.1 Volume expansion and water retention capacity

Compressed coco discs were allowed to expand by adding water and VE was calculated as the ratio of final volume to the initial volume. WRC was determined as the maximum amount of water that could be absorbed per unit weight of compressed coco disc.

3.2.2 Electrical conductivity and pH

Coco discs were wetted to the saturation limit using distilled water. Thereafter 300ml of distilled water was added for each 50 ml of wetted coco disc sample and the mixture was stirred for 1 hour on a mechanical shaker. The filtrates of these samples were used to measure the pH and EC using pH meter (Hach, HQ 40 D, USA) and EC meter (Hach, MM150, USA), respectively.

3.3 Mechanical Properties of Coco Discs

Compaction ratio (CR) was measured as the ratio of bulk density of coco disc to the bulk density of coir pith.

3.4 Scanning Electron Microscopy (SEM) Analysis

Microstructure of the coir pith samples was examined using Scanning Electron Microscope (LEO, 1420vp, England).

3.5 Analysis of the Drying Process

3.5.1 Specific moisture extraction rate (SMER)

Dryer efficiency was determined in terms of specific moisture extraction rate (SMER) which is a measure of the efficiency of energy usage. It is defined as the ratio of the amount of water evaporated from the product to the energy required for that evaporation and determined from Eq. [3.4].

$$SMER = {M_t}/{(P_{bl} + W * C)} \quad [3.4]$$

$M_t = Amount\ of\ water\ evaported\ during\ the\ drying\ process$

$P_{bl} = Amount\ of\ energy\ consumed\ by\ the\ blower$

$W = Amount\ of\ kerosene\ used\ by\ the\ burner$

$C = Calorific\ value\ of\ kerosene$

3.5.2 Estimation of effective moisture diffusivity

The drying processes are governed by internal mass transfer resistance. Fick's second law for diffusion can be used for the determination of drying characteristics of biological materials in the falling rate period (Arslan and Ozcan, 2010; Maskan et al., 2002). The general series solution of Fick's second law for spherical co-ordinates under the assumption of constant moisture diffusivity and temperature, and also the negligible shrinkage is given by Eq. [3.5].

$$\frac{M-M_e}{M_0-M_e} = \frac{6}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{i^2}\exp\left(-\frac{i^2\pi^2 D_{eff} t}{r^2}\right) \qquad [3.5]$$

Where D_{eff} is the effective moisture diffusivity (m^2/s) and *r* is the radius of sphere.

For relatively longer drying time, Eq. [3.5] can be simplified as

$$ln\left(\frac{M-M_e}{M_0-M_e}\right) = ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{r^2}\right)t \qquad [3.6]$$

Effective moisture diffusivity can be calculated from the gradient of Eq. [3.6].

3.6 Statistical Analysis

3.6.1 Statistical Significance

One-way analysis of variance (ANOVA) was used to determine the statistical significance of the parameters using SAS 9.1.3 software.

3.6.2 Nonlinear regression analysis

Nonlinear regression analysis was performed using "Lab fit' software and the statistical parameters of coefficient of determination (R^2), root mean square error (RMSE) and reduced chi-square ($\chi 2$) were compared among the mathematical models to examine the validity.

The coefficient of determination (Eq. [3.7]) is a primary criterion used to identify the best fit (El-Mesery and Mwithige, 2012). In addition to R^2, root mean square error (Eq. [3.8]) and reduced χ^2 (Eq. [3.9]) can also be used to determine the appropriateness of the fit (Sarasavadia, 1999). For quality fit, R^2 should be close to 1 while the values of the RMSE and reduced χ^2 should be close to zero (Togrul and pehlivan, 2002; Erenturk et al, 2004; Demir et al., 2004; Goyal et al., 2006).

Considering the non-linear behavior of mathematical models listed in Table 8.1, the mean relative deviation modulus (E %) was also calculated to evaluate the accuracy of the fit using Eq. [3.10]. Value of E% smaller than 5 indicates an extremely good fit; a value between 5 and 10 represents a reasonably good fit; and a value greater than 10 shows a poor fit (Lomauro et al., 1985a, b; Gencturk et al., 1986).

(A) Coefficient of determination (R^2)

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)\right]^2 * \left[\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)\right]^2}} \qquad [3.7]$$

(B) Root mean square error (RMSE)

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i}-MR_{exp,i}\right)^2\right]^{1/2} \qquad [3.8]$$

(C) Reduced chi-square (χ2)

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-n} \qquad [3.9]$$

(D) Mean relative deviation modulus (E %)

$$E(\%) = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{Experimental\ value - Predicted\ value}{Experimental\ value}\right| \qquad [3.10]$$

Where

$MR_{exp,i}$ and $MR_{pre,i}$ are the actual and predicted moisture ratios, respectively

N is the total number of observations and n is the number of constants in the model.

CHAPTER FOUR

4.0 MATERIALS AND METHODS

4.1 Materials

Raw coir pith samples were collected from 6 different mills located in Puttlam District in Sir Lanka for the analysis of the quality variations in coir pith with respect to the method of retting and extraction. About 150 dry coconut husks, obtained from Lunuwila, Sri Lanka were used to examine the effect of retting time. Raw coir pith samples collected from a coir mill at Lunuwila in Sri Lanka were used for the preliminary investigations and to examine the drying characteristics and the quality variation of coir pith under the different drying methods; sun drying, oven drying, hot air drying and flash drying.

4.2 Equipment

D1 method and Ceylon Drum method were used for fibre extraction. In D1 method husks are half broken by spikes, fitted to a rotating drum. The half broken husks are then transferred to a turbo cleaner in order to defibre by means of beaters, fitted to the main shaft of turbo cleaner. In Ceylon Drum method breaking and cleaning of husks are done by means of spikes, fitted to two rotating drums called breaker drum and cleaner drum.

Drying experiments were performed in laboratory scale with the use of hot air dryer, oven (SANYO Gallenkamp PLC, OPL25.DTI-C, UK) and a pilot scale flash dryer.
Anemometer (Lutron, LM 8100, Taiwan) was used to measure the velocity. A special sieve set (Retsch, AS 200, Germany) was used to determine the particle size distribution. Scanning electron microscope (LEO, 1420vp, England) was used to analyze the microscopic structure.

4.2.1 Hot air dryer

A laboratory scale hot air dryer (Figure 4.1) was used with a separately fabricated drying chamber with an accuracy of ±1 ºC. Drying chamber (1x1x1 ft^3) was fabricated using stainless steel plates with a wire mesh of 0.5 mm placed at the bottom to facilitate the air flow and to retain the coir pith. Top of the chamber was fitted with a hinged wire mesh of 0.5 mm to avoid entrainment of coir pith. A glass plate was fixed to the front side to observe the fluidizing and circulating effect (particle motion) of coir pith. Damper was used to regulate the air flow to the blower and thereby control the air flow in the drying chamber.

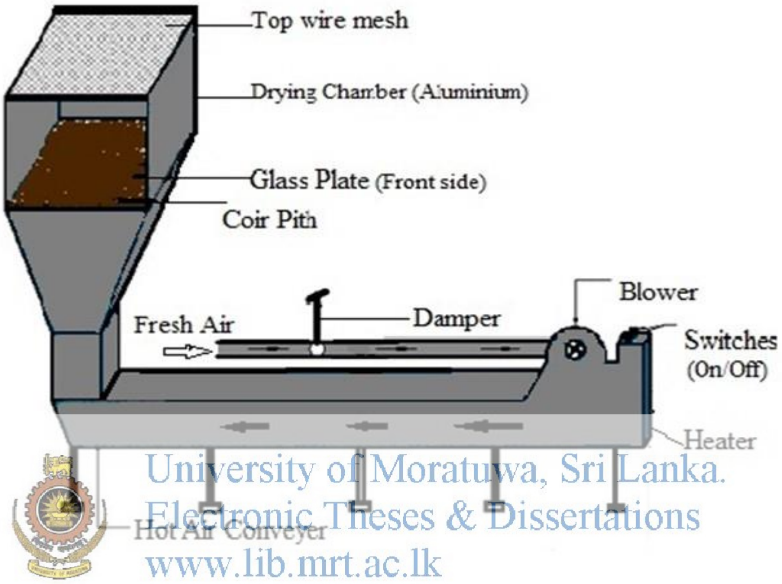

Figure 4.1: A schematic diagram of hot air dryer

4.2.2 Pilot scale flash dryer

A pilot scale flash dryer with a conveying duct having 10 m in length and 2.1 m in height was fabricated. This unit is consisted with a hot gas generator (kerosene oil burner), a blower (3 hp), a hot gas conveying duct, a venturi located just below the feeding point and cyclone separator as illustrated in Fig. 4.2. Hot gas was conveyed at a maximum velocity of 32.0 ± 0.15 m/s using a blower (3 hp). A temperature controller was placed just before the feeding point to maintain the temperature of coir pith at a constant level. The moisture content of coir pith was reduced due to flashing effect from the sudden pressure drop at the venturi and also due to convective heat and mass transfer while passing through the hot air conveying duct.

Cyclone separator was used to separate dried coir pith from the moist air and the dried coir pith was collected at the exit (bottom).

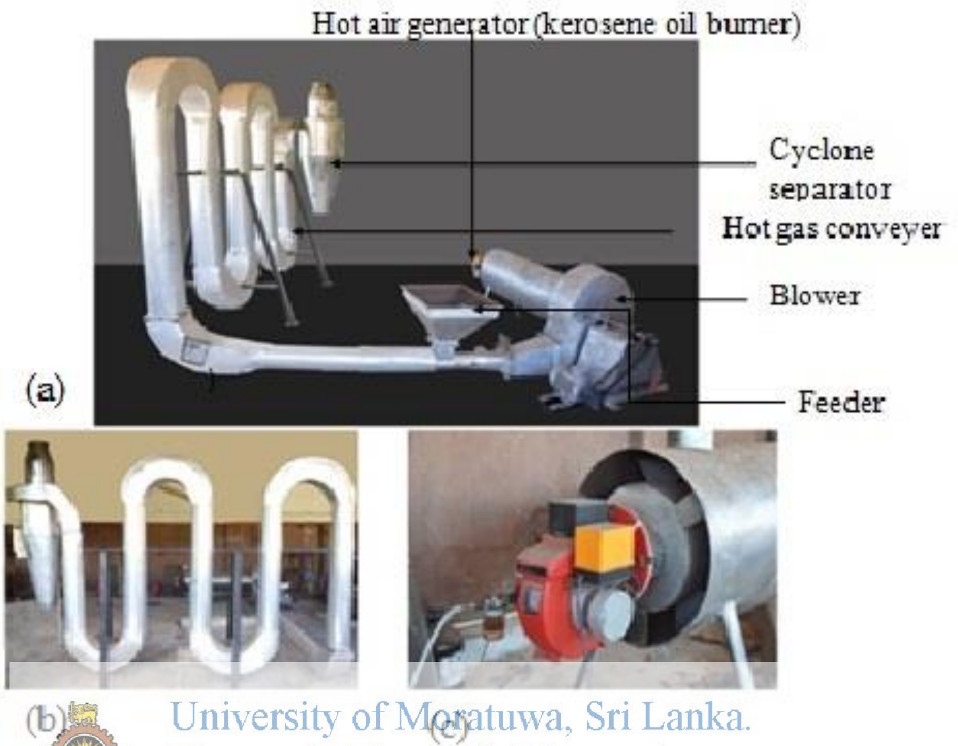

Figure 4.2: (a) Locally fabricated flash dryer, (b) End view of flash dryer c) Hot air generator (kerosene oil burner)

4.3 Methods

Preliminary work was carried out to identify the most suitable range of particle size and moisture content to produce coir pith products with acceptable quality for export market and also to find the optimum temperature to dry coir pith. Separate experiments were carried out to examine the quality analysis of coir pith products with reference to

- Effect of retting time and the method of retting
- Effect of drying technique

A new mathematical model was developed to describe the thin layer drying of coir pith and the model was validated.

Pilot scale flash dryer was designed and fabricated as described in section 4.2.2. Experiments were carried out to examine the performance of the flash dryer and the quality analysis of coir pith products was carried out to compare the flash and sun drying techniques.

The results of the preliminary work are discussed in Chapter 5. The evaluation of the effect of time duration and method of retting on the quality variations of coir pith and coco discs are discussed in Chapter 6. The results of the study on drying techniques are given in Chapter 7. The analysis of mathematical model and the results of validation experiments are given in Chapter 8. The results of flash drying experiments are discussed in Chapter 9.

4.3.1 Preliminary work

4.3.1.1 Effect of the range and distribution of particle size on the volume expansion ratio of coco discs

Sieves with mesh sizes 1/6, 1/4 and 1/2 inches (4.23, 6.35 and 12.7 mm, respectively) were used along with the mesh size 0.5 mm in this study. Coir pith samples (4 kg) having moisture content of 376 ± 2% (w/w, dry basis) were sun dried to achieve moisture content of 22-25% (w/w, dry basis). Coir pith particles were grouped as 0.5 - 4.23 mm, 0.5 - 6.35 mm and 0.5 -12.7 mm. Samples from each group were used to prepare compressed coir pith discs (coco discs) by compressing under 1500 psi using a hydraulic press. The specifications of coco discs were, height 24 ± 1 mm, diameter 78 ± 1 mm and weight 60 ± 2 g. Volume expansion ratios were measured by following the standard method given in Sri Lanka Standards (SLSI, 2001). All the experiments were triplicated.

The effect of particle size distribution on the volume expansion of coco discs was also examined. The particles in the range of 0.5 – 4.23 mm were selected for this analysis. This range was subdivided into 3 groups with the ranges of particle sizes 0.5 – 1.0 mm, 1.0 – 2.0 mm and 2.0 – 4.23 mm by using additional sieves with mesh sizes 1 mm and 2.0 mm. Different particle size distributions of the range 0.5 – 4.23 mm was then obtained by having several combinations of the subdivided groups as indicated in Table 5.1. A similar procedure as in the case of analyzing the effect of the range of particle size was followed in this analysis also.

Verification of the results was done by analyzing the volume expansion of coco discs manufactured by 4 different exporters of coir pith products.

4.3.1.2 Effect of drying temperature on volume expansion ratio of coco discs

Coir pith samples of 700 ± 5 g each were oven dried at temperatures in between 100 – 240 °C at intervals of 20 ºC. In industrial practice, the final moisture content of coir pith before compaction was found to be 15 ± 5% (w/w, dry basis). Therefore a final moisture content of 17 ±1 % (w/w, dry basis) was selected and the drying time for each experiment was recorded. The dried samples were then sieved using 1/4 inch and 0.5mm mesh sizes and then compressed at 1500 psi using a hydraulic press, into the form of discs. The volume expansion ratio of these compacted discs was measured in order to determine the optimum drying temperature.

4.3.1.3 Effect of the moisture content of dried coir pith on volume expansion ratio of coco discs

Samples of 1 kg of raw coir pith were sieved using 1/2 inch mesh size net and were dried in an oven at 140 °C to achieve several samples having moisture contents in the range of 11-12%, 12-17%, 17-23%, 23-33% and >33%. Dried samples were then sieved using 1/4 inch and 0.5mm mesh sizes and then compressed at 1500 psi using a hydraulic press, into the form of discs. The volume expansion of these compacted discs was measured in order to determine the optimum moisture content in the dried coir pith.

4.3.2 Effect of time duration of retting and method of retting

4.3.2.1 Experiments on retting time

About 150 dry coconut husks were retted in a tank and Ceylon Drum method was used for fibre extraction. Thirty husks were used at a time to obtain coir pith and five replicated samples of 700 ± 2 g were randomly selected. Each sample was separately sun dried to achieve the moisture content of 16 - 17% (w/w, dry basis). Coco discs were made by compressing the dried coir pith using hydraulic press machine under 1500 psi. Coco discs with five replicates were used to determine the quality parameters of pH, electrical conductivity, volume expansion and water retention capacity according to the Sri Lanka Standards (SLSI, 2001).

Since coir pith is a byproduct of coir fibre manufacturing process, the effect of retting on the quality variations in coir fibre was also examined with triplicated experiments. For the determination of length and breaking load, 4 samples, each with 2 g of coir fibre, were grouped into the relevant length fraction of 0 - 100 mm, 101 - 200 mm and more than 200 mm. No of fibres in each length category and their weight were recorded. In addition to that diameters of 30 fibres in each category were also measured. Using the Tensile Strength Tester (Admet, Expert 5601 SM 100, USA) breaking load and the elongation of 10 fibres in each length category were measured.

4.3.2.2 Experiments on method of retting

Coir pith samples obtained from six different mills practicing different methods of retting were examined in this study. Table 4.1 summarizes the pre-processing methods practiced by each mill. The six mills in Table 4.1 are categorized into two types, according to the method of extraction, namely D1 method and Ceylon Drum method. It shows that average moisture contents of the coir pith samples collected from these mills are significantly different. This is mainly attributed to the differences in retting practice. Two of the mills (mill 1 & mill 2) used raw coconut husks (green husks) and the others used dry coconut husks (brown husks) for their operations. Retting was performed by steeping the husks in water for longer periods (from 1 month to 4 months) and soaking was performed by steeping the husks for shorter period of 1 week. Water spraying was done mainly using a rubber horse at a rate of 6 - 8 l/min for 3 times a day while sprinkling was done using a sprinkler system at a rate of 1 - 2 l/min which was operating continuously for 1 day.

Five coir pith samples were randomly selected from each mill and were analyzed for particle size distribution, microorganisms and physiochemical properties of coco discs by following the methods described in Chapter 3. In addition to that drying characteristics of the coir pith samples obtained from the 6 different mills were analyzed using the method of sun drying.

Table 4.1: Pre-processing of coconut husks and moisture content of raw coir pith

Mill No	Method of Extraction	Pre-processing Methods	Average moisture content of coir pith% (w/w, dry basis)
1	D1 Method	Intermittent water spraying three times a day for 1 day	328 ± 1^{a}
2		Continuous Water sprinkling for 1 day	350 ± 3^{b}
3		Soaking up to 7 days	194 ± 2^{c}
4	Ceylon Drum Method	Retting (1 month) after crushing the husk	463 ± 2^{d}
5		Retting (3 months)	416 ± 2^{e}
6		Retting (4 months)	502 ± 1^{f}

Means with different superscript within the same column are significantly different from each other at $p < 0.05$ level.

Coir pith was sun dried using (40x30x6 cm^3) trays in which samples were filled only up to 2 cm (700 ± 5 g) to have thin layers. Moisture loss of coir pith was recorded at one-hour time intervals using a digital balance (Shimadzu, BX –K/BW-K, Japan) with the measurement range of 0 – 16.5 kg and an accuracy of ±1 g. The samples were properly mixed in one-hour time intervals to maintain uniformity. Drying was continued until the moisture content was reduced to 16 – 17% (w/w, dry basis). Experiments were triplicated for obtaining more accurate results. Temperature and relative humidity were also recorded just above the coir pith at each time using a thermometer with hygrometer (Easy view 25, China).

4.3.3 Effect of drying techniques

The effect of drying technique in the quality variations of coir pith was studied. Three different drying techniques namely, sun drying, oven drying and hot air drying were compared. All the experiments on drying techniques were replicated 5 times

4.3.3.1 Sun drying and oven drying

Coir pith samples of 300 ± 2 g were dried as a thin layer (about 2 cm) for both sun drying and oven drying. Aluminium trays were used for sun drying under the atmospheric conditions; temperature of 29 ± 2 °C, relative humidity of 6 0 ± 5% and solar intensity of 13 - 15 MJ/m^2. Oven drying was carried out at 140 °C in an oven (SANYO Gallenkamp PLC, OPL25.DTI-C, UK) with an accuracy of ± 1°C.

4.3.3.2 Hot air drying

Drying experiments were performed to determine the effect of velocity on the drying of coir pith at constant temperature. Different air flow rates of 0.025, 0.020 ,0.017 and 0.014 m^3/s with an accuracy of ± 0.001 m^3/s and constant temperature of 140 ± 1 °C were used for drying coir pith samples of 300 ± 1 g each to achieve the final moisture content of 16 - 17 % (w/w, dry basis).The initial moisture contents of fresh coir pith samples were found to be 488 ± 1% (w/w, dry basis). All the experiments were conducted with four replicates. The weight loss of the samples during drying was measured using an electronic balance (DENVER, TP 3002, Germany) with an accuracy of ± 0.01 g. The drying characteristics of coir pith were examined using the drying curves and the instantaneous drying rate, DR (g water /g dry matter per min), was calculated using Eq. 4.1.

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad [4.1]$$

Where

M_{t+dt} - Moisture content at time $t + \Delta t$ (kg water/kg dry matter)

M_t - Moisture content at time t (kg water/kg dry matter)

4.3.4 Mathematical modeling for thin layer drying

Semi-theoretical models are widely used in describing thin layer drying and they are generally derived by simplifying general series solutions of Fick's second law or modification of simplified diffusion models. These models describe the variation of the non-dimensional parameter *MR* (Eq. [3.3]) with time. Newton model (Eq. [4.2]), Page model (Eq. [4.3]), modified Page model (Eq. [4.4]), Diffusion approximation model (Eq. [4.5]), Wang and Singh model (Eq. [4.6]) and Linear model (Eq. [4.7]) were used in several studies to describe the thin layer drying of food and agricultural materials (Botheju et al, 2011, Panchariya et al, 2002, Tiris et al, 1994, Kaushal and Sharma, 2014). In the present study, drying kinetics of coir pith was studied using these models. A new model (Eq. [4.8]) was also proposed and validated.

$$MR = exp(-kt) \qquad [4.2]$$

$$MR = exp[-kt^n] \qquad [4.3]$$

$$MR = exp[(-kt)^n] \qquad [4.4]$$

$$MR = a\exp(-kt) + (1-a)\exp(-kbt) \qquad [4.5]$$

$$MR = 1 + at + bt^2 \qquad [4.6]$$

$$MR = a + bt \qquad [4.7]$$

$$MR = (1 + at + bt^2)/(1 + ct) \qquad [4.8]$$

Where

MR is the moisture ratio, *t* is the time and, *k*, *a*, *b*, *c* and *n* are constants

4.3.5 Flash drying of coir pith

4.3.5.1 Experiments on flash drying

Fresh coir pith samples of 5 kg each were used in flash drying experiments. The flash drying temperatures were selected in the range of 120 to 160 °C at the intervals of 10 °C. The average velocity across the hot air conveying duct was measured and the minimum air velocity required to convey the fresh coir pith within the hot gas conveyor was found to be 26.1 ± 0.2 m/s. The maximum air velocity of 32.0 ± 0.15 m/s could be achieved with the full load capacity of the blower motor used in the current study. Therefore these two velocities were selected for the analysis. Coir pith samples having the initial moisture content of 318 ± 2 % (w/w, dry basis) were fed into the feeder and hot air was used to convey the coir pith. Heat was generated by the burner and the temperature of hot air was controlled with an accuracy of ± 1 °C. Coir pith was collected at the exit of the cyclone separator.

The flash drying cycle was defined as the distance between the feeding point and the collecting point of the coir pith.

Recycling was proceeded until the moisture content reached in between 18% and 23% (w/w, dry basis). Final moisture content and the time taken for each cycle were recorded. Experiments were replicated 3 times. The quality of flash dried coir pith was compared with that of sun dried coir pith. SEM analysis and microbial analysis of flash dried coir pith and the energy analysis in terms of SMER for the pilot scale flash dryer were examined. The effect of temperature on reduction of microbial count in flash dried coir pith was examined at the end of each cycle for the temperatures of 120, 140 and 160 °C.

4.3.5.2 Comparison with sun drying

Coir pith samples of 700 ± 5 g were laid on Aluminium trays in an area of 1.5 x 1 ft^2 and were dried as thin layer of 2 cm in direct sun light under atmospheric conditions; temperature 30±2 °C, relative humidity 55± 5% and solar intensity 13 -15 MJ/m^2. Coir pith was mixed well at 1 hr time intervals to ensure the uniformity. Coir pith drying was performed until it reached the moisture content in between 12% and 17% (w/w, dry basis). The experiments were replicated 5 times.

CHAPTER FIVE

5.0 PRELIMINARY WORK

5.1 Background

As quality of the compressed coir pith depends on different measures, preliminary investigations were carried out to evaluate the best range of particle sizes to be used for manufacturing compressed coco discs, optimum temperature for drying of coir pith and the suitable range of moisture content of dried coir pith to achieve good quality products which gives the highest volume expansion ratio.

5.2 Results and Discussion

5.2.1 Particle size range and distribution on quality of coir pith products

Figure 5.1 shows the results of volume expansion for 3 different ranges of particle sizes. The results indicate that volume expansion was reduced with the increase of the range of particle sizes where large particles were also included. These large particles were mostly fibres.

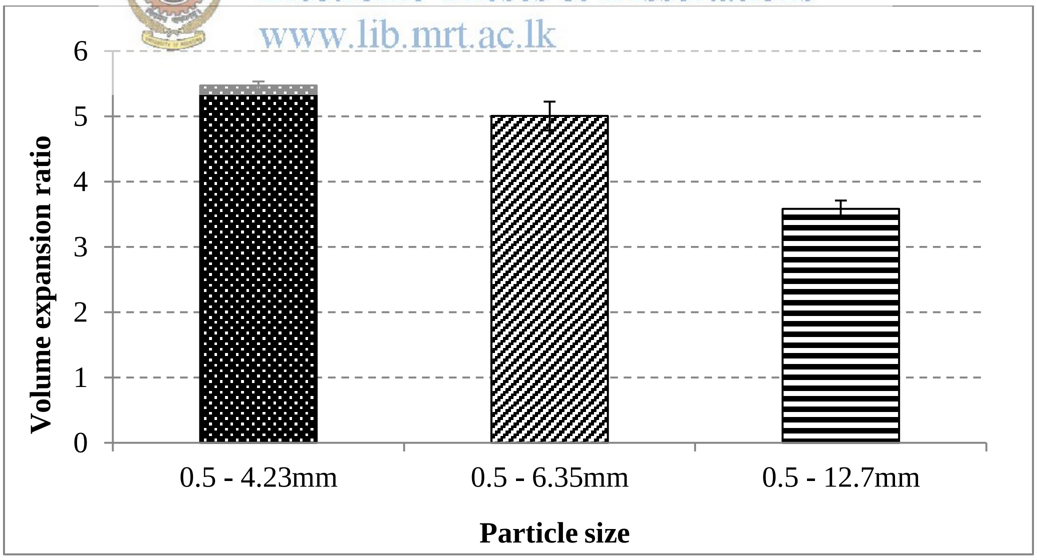

Figure 5.1: Volume expansion ratio for different range of particle sizes

According Table 5.1, percentage of usable coir pith had only marginally increased but the volume expansion (Figure 5.1) had significantly decreased by widening the range of particle sizes from 0.5 – 6.35 mm to 0.5 – 12.7 mm. On the other hand, the increase of volume expansion was only marginal when the rough particles were narrowed down from 0.5 – 6.35 mm to 0.5 – 4.23 mm.

Table 5.1: Percentage of usable coir pith for different range of particle sizes

Particle size range (mm)	**0. 5 - 4.23**	**0.5 - 6.35**	**0.5– 12.7**
Usable coir* pith (D1 method)	86%	89%	91%
Usable coir* pith (Ceylon Drum method)	87%	90%	93%

$$*Usable\ coir\ pith(\%) = \frac{Amount\ of\ coir\ pith\ used\ for\ product\ making}{(coirpith + fiber\ waste)}\ x\ 100$$

The results of the volume expansion for different particle size distributions as indicated by the Combinations 1 – 7 are given in Table 5.2. The combinations 3 and 5 having high percentage (≥ 40%) of large particles gave significantly low volume expansion values. The combination 6 is also having 40% of large particles but it also has 40% of medium particles and hence gave a high volume expansion.

Table 5.2: Results of volume expansion for different combinations of particle sizes

Combination	**0.5 – 1.0 mm**	**1.0 – 2.0 mm**	**2 - 4.23 mm**	**Volume Expansion**
1	1	1	1	5.14 ±0.44[a]
2	1	2	1	5.24±0.27[a]
3	1	1	2	4.61±0.11[b]
4	2	1	1	5.22±0.08[a]
5	2	1	2	4.64±0.12[b]
6	1	2	2	5.27±0.19[a]
7	2	2	1	5.13±0.22[a]

Means with different superscript within the same column are significantly different from each other at $p < 0.05$ level.

The results of this study suggest that particles larger than 6.35 mm (mesh size of ¼ inch) are not suitable for manufacturing compressed coir pith products. Further reduction to less than 4.23 mm improves the volume expansion only marginally. Therefore the size range 0.5 – 6.35 mm is recommended for the production of compressed coir pith products. It can be further recommended to have higher percentage of medium and small size particles within the particle size distribution of the selected range.

In fact, currently most of the manufacturers of compressed coir pith products use the size range of 0.5 – 6.35 mm. The comparison of the volume expansion for 4 different manufacturers of coco discs is given in Table 5.3.These results indicate that volume expansion of coco discs vary among the manufacturers even if they use the same range of particle sizes. Difference in particle size distribution is one important factor for the change in volume expansion. Other factors can be identified as the retting time, storage conditions, crushing before fibre extraction and method of fibre extraction. However, method of fibre extraction (D1 method or Ceylon Drum method) has only a marginal effect on the percentage of usable coir pith as can be observed in Table 5.1.

Table 5.3: Volume expansion for coco discs produced by different manufacturers

Manufacturer	Range of particle sizes	Volume Expansion
1	0.5 – 6.35 mm	5.42 ± 0.39^{ab}
2	0.5 – 6.35 mm	5.30 ± 0.37^{a}
3	0.5 – 6.35 mm	6.32 ± 0.55^{b}
4	0.5 – 6.35 mm	5.51 ± 0.52^{ab}

Means with different superscript within the same column are significantly different from each other at $p < 0.05$ level.

5.2.2 Optimum drying temperature

The volume expansion of compacted discs after adding water was used as the basis for finding the optimum drying temperature. Table 5.4 summarizes the results of volume expansion and drying time for samples dried at different temperatures. Results clearly indicate that drying at low temperatures gave higher volume expansion but at the expense of drying time. Based on the statistical significance at a confidence level of $p < 0.05$, results of volume expansion can be categorized into two groups; drying temperature of ≥ 160 °C and the drying temperature of ≤ 140 °C.

Therefore 140 °C was selected as the optimum drying temperature by considering both the high volume expansion and the low drying time.

Table 5.4: Volume expansion of coir pith dried under different drying temperatures

Temperature(^{o} C)	Volume Expansion	Drying Time (min)
240	3.8 ± 0.23^{a}	32
220	4.12 ± 0.11^{a}	36
200	3.96 ± 0.15^{a}	47
180	4.16 ± 0.21^{a}	58
160	4.41 ± 0.83^{a}	71
140	5.61 ± 0.25^{b}	105
120	5.72 ± 0.31^{b}	195
100	5.96 ± 0.22^{b}	300

Means with different superscript within the same column are significantly different from each other at $p < 0.05$ level

5.2.3 Determination of optimum moisture content

Dried coir pith with the moisture contents in between 12 and 23% (w/w, dry basis) had exhibited high volume expansion ratio (> 5) as shown in Figure 5.2. Therefore the moisture content of dried coir pith in the range of 12 – 23% (w/w, dry basis) is recommended for the manufacturing of coco discs.

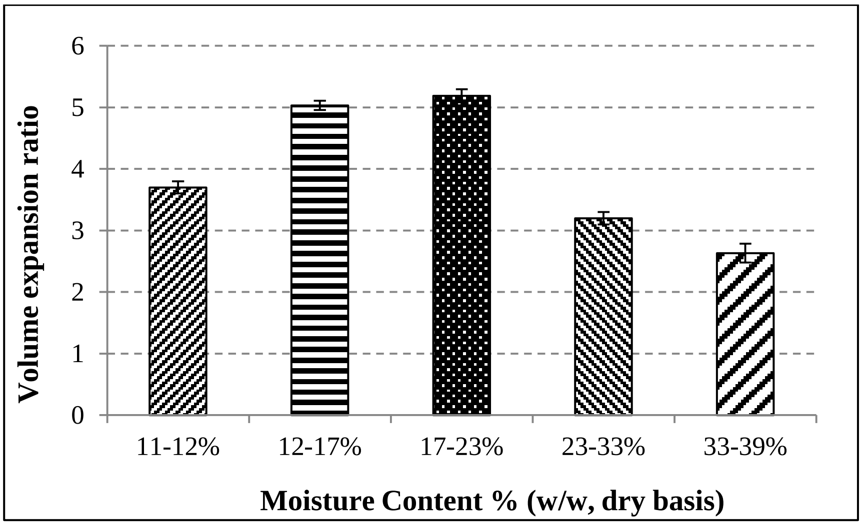

Figure 5.2: Volume expansion ratio for different moisture contents of dried coir pith

CHAPTER SIX

6.0 EFFECT OF METHOD AND TIME DURTION OF RETTING ON QUALITY OF COIR PITH

6.1 Background

Method of extraction, area of cultivation and aging were found to influence the composition, particle size distribution and the physicochemical properties of coir pith (Moorthy and Rao, 1998; Tharanga et al., 2005). The increase in particle size leads to decrease in the porosity, density, absorptivity and electrical conductivity whilst increasing the pH of raw coir pith (Ross et al., 2012). Particle size distribution of coir pith may also be influenced by the method of preprocessing of coconut husks namely, crushing, soaking, water spraying and retting. Quality variations of coir pith samples were analyzed with respect to the time duration and the method of retting.

6.2 Results and discussion

6.2.1 Effect of time duration on retting

Figure 6.1 indicates that the most important properties of coco discs namely volume expansion and water retention capacity, are notably increasing with retting time. Statistical Analysis (ANOVA) confirmed that variation of volume expansion was statistically significant within the entire period from 4 weeks (VE of 3.71±0.07) to 12 weeks (VE of 5.77±0.19) of retting time. Even though the variation of water retention capacity from 4 weeks to 8 weeks was not statistically significant, a significant increase in water retention capacity could be observed from 8 weeks (WRC of 3.43±0.12) to 12 weeks (WRC of 5.87±0.35). Retting process leads to degrading of coarse coir pith particles into small and medium size particles having numerous numbers of pores. Consequently particle size distribution becomes narrow and the specific surface area of coir pith particles increases. According to Jayaseeli and Raj (2010) high specific surface area contributes to high water retention capacity. A similar explanation holds for the volume expansion.

Figure 6.1 also depicts that pH of coir pith has significantly reduced from 6.50 ± 0.11 in 4 weeks to 5.97 ± 0.12 in 6 weeks. The change in pH with further retting was not significant and pH of coir pith for the entire period of retting was found to be within the standard of 4.5 to 6.8 (SLS, 2001). Presence of potassium ions increases the pH while polyphenolic compounds decrease the pH. The slight reduction in pH may be attributed to the leaching out of both potassium ions and polyphenolic compounds from husks during retting. On the other hand, electrical conductivity has significantly dropped with the period of retting. The reduction of potassium ions in coconut husk might have mainly contributed to the change in electrical conductivity. The change in EC was from 109 ± 7μs/cm in 4 weeks to 63 ± 8μs/cm in 12 weeks and the values were within the standard of less than 500μs/cm (SLSI, 2001).

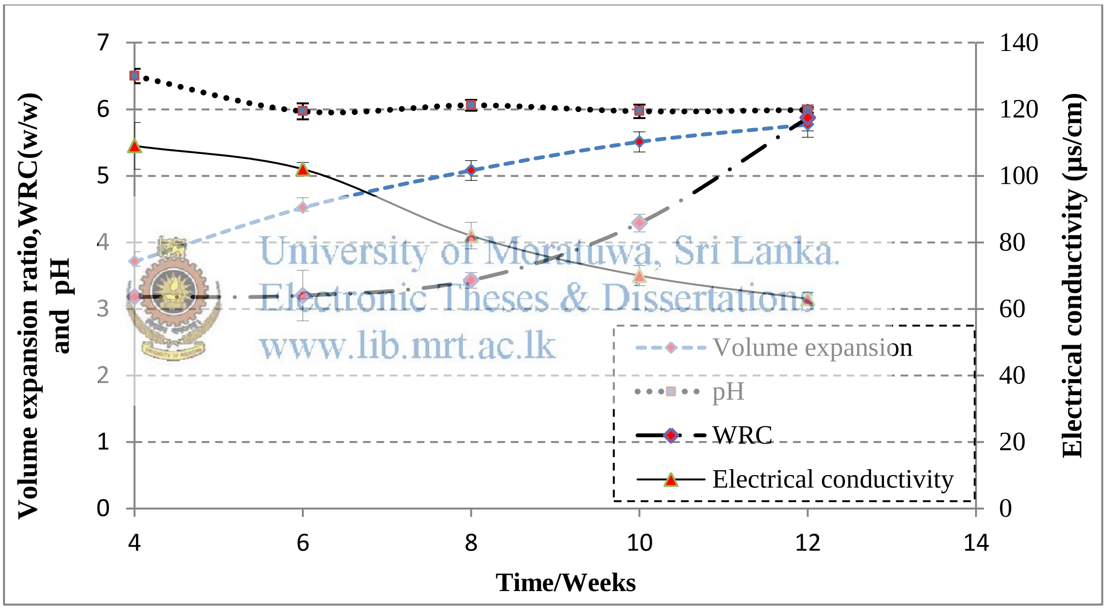

Figure 6.1: Quality variation of coir pith with retting time

Table 6.1 summarizes the effect of retting time on length, tensile strength and breaking load of coir fibre and the test reports are attached in Appendix A 1- A 5. Retting is a microbial process leading to degradation of pectin and poly-phenolic compounds in coir fibre. It is a natural process and facilitates the extraction of coir fibre (Ravindranath, 2001). Table 6.1 indicates that all the important properties relevant to coir fibre are notably improving with retting time. However, comparable properties could be obtained with lesser retting time of 4 weeks as compared to 3 months of conventional retting, by crushing the husks before retting (Appendix A5 and A6). In Sri Lanka most of the coir fibre mills practise conventional retting of husks for 3 months and some of the mills are now operating with lesser retting time by crushing the husks before retting.

Table 6.1: Quality parameters of coir fibre with respect to the retting time

Quality parameter	**Time duration of retting**					
	4 weeks	6 weeks	8 weeks	10 weeks	12 weeks	4 weeks after crushing husks
Length/mm	133±1	136±2	142± 19	168±6	182± 9	186± 7
TS*/N/mm^2	81± 7	84± 7	88± 8	92±1	104± 12	109± 7
BL**/ N	3.58± 0.42	3.61± 0.11	3.62± 0.19	3.65±0.07	4.32± 0.38	4.23±0.24

*TS= Tensile Strength, **BL= Breaking load

6.2.2 Effect of method of retting

6.2.2.1 Drying characteristic of coir pith

Figures 6.2 and 6.3 show the drying curves for coir pith of D1 method and Ceylon Drum method respectively. A very short constant rate period followed with a long falling rate period could be observed. Even the initial moisture contents were notably different among the mills, drying periods required to achieve the final moisture content of 16 – 17% (w/w, dry basis), were not significantly different (12 ± 1 hours). However, coir pith obtained from D1 method dried slightly faster than the coir pith obtained from Ceylon Drum method.

6.2.2.2 Particle size distribution of coir pith

Figure 6.4 shows the particle size distribution of coir pith obtained from the two different types of fibre extraction methods namely, D1 method (Mills 1,2 and 3) and Ceylon drum method (Mills 4, 5 and 6). Results indicate that for a given method of extraction, amount of fine particles has increased with the increase of retting time.

Longer period of retting is necessary for Ceylon Drum method but water spraying or sprinkling is sufficient for D1 method. Even though Mill 4 used Ceylon Drum method for fibre extraction, retting time was limited to one month. However, Mill 4 used an additional processing step of crushing before retting. As a result it had the coir pith with the highest amount of medium size particles (about 85%).

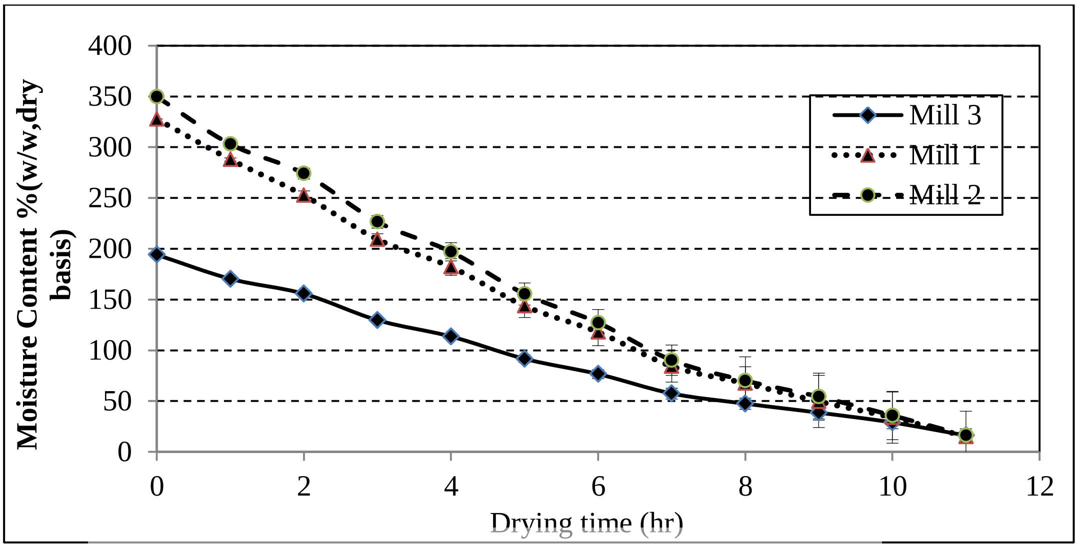

Figure 6.2: Varition of moisture content vs time for D1 method

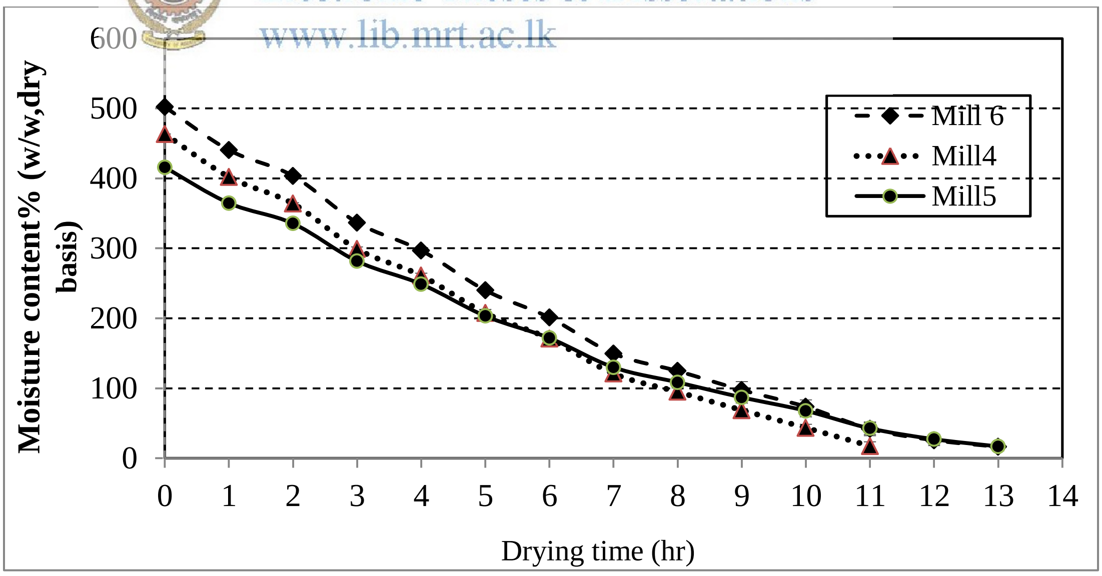

Figure 6.3 : Varition of moisture content vs time for Ceylon Drum Method

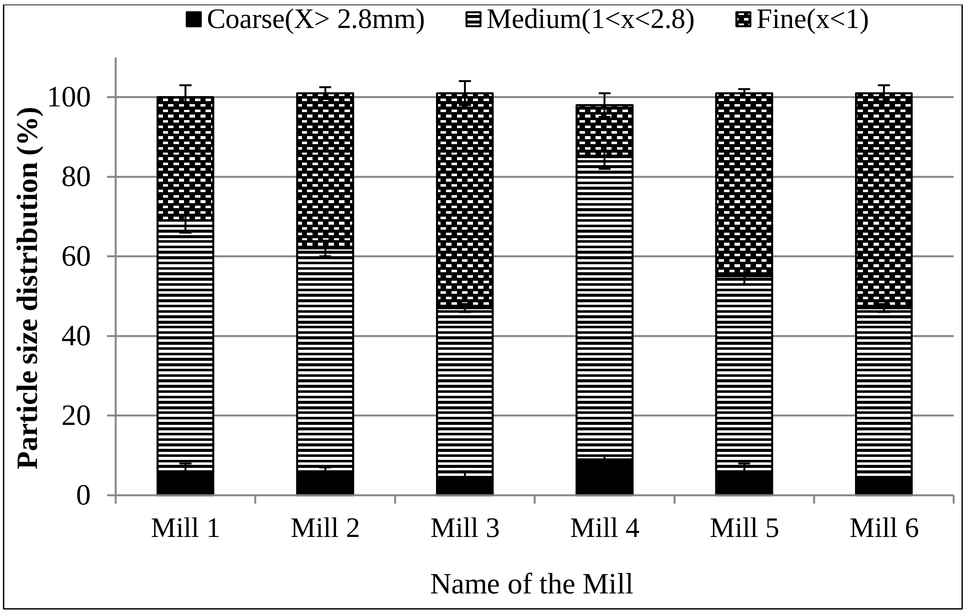

Figure 6.4: Particle size distribution of coir pith

6.2.2.3 Physicochemical properties of coco discs

The results of section 6.2.1 clearly indicate that retting time has a significant effect on the properties of coir pith. Method of extraction is a physical process and it has high influence on particle size distribution as can be seen in Figure 6.4. However, the results for the analysis of properties of coco discs given in Table 6.2 indicate that even if different methods of retting and extraction were used, coir pith obtained from different mills had similar properties. ANOVA test confirmed that results were not statistically significant. The only exception was the electrical conductivity of coir pith from mill 1. Mill 1 had high EC due to the salinity of spraying water as it was close to the sea. Therefore, the observation of similar properties in coco discs from different mills might have attributed mainly to randomness of raw coconut husks. Unlike for the controlled experiments, raw husks for the mill operations were random in nature due to several reasons including variety of coconut husks, agro-ecological zones from where husks were collected, degree of the variation in environment conditions such as drying in sun light and exposing to rain etc.

Table 6.2: Physicochemical properties of coco discs

Mill No.	Method	VE	WRC(w/w)	pH	EC(μs/cm)
1	D1 method	6.1 ± 0.44^{a}	6.2 ± 0.43^{a}	5.8 ± 0.53^{a}	787 ± 57^{b}
2		5.2 ± 0.63^{a}	4.5 ± 0.73^{a}	5.6 ± 0.61^{a}	402 ± 137^{a}
3		5.3 ± 0.53^{a}	5.6 ± 0.62^{a}	6.0 ± 0.41^{a}	612 ± 103^{a}
4	Ceylon Drum method	6.3 ± 0.62^{a}	5.9 ± 0.23^{a}	5.8 ± 0.21^{a}	577 ± 101^{a}
5		5.4 ± 0.57^{a}	5.9 ± 0.46^{a}	6.1 ± 0.23^{a}	490 ± 99^{a}
6		5.9 ± 0.51^{a}	6.4 ± 0.51^{a}	5.7 ± 0.55^{a}	386 ± 123^{a}

Means with same superscript within the same column are not significantly different from each other at $p > 0.05$ level

6.2.2.4 Microbial content

Microbial analysis revealed that the initial microbial content of coir pith obtained from Ceylon Drum method was about 10 times greater than that of D1 method. Significantly high initial microbial content of Ceylon Drum method is mainly attributed to higher number of microbes involved in the retting pit. Figure 6.5 shows the variation of plate count over drying time for two samples, each representing D1 method (mill 2) and Ceylon Drum method (mill 6).

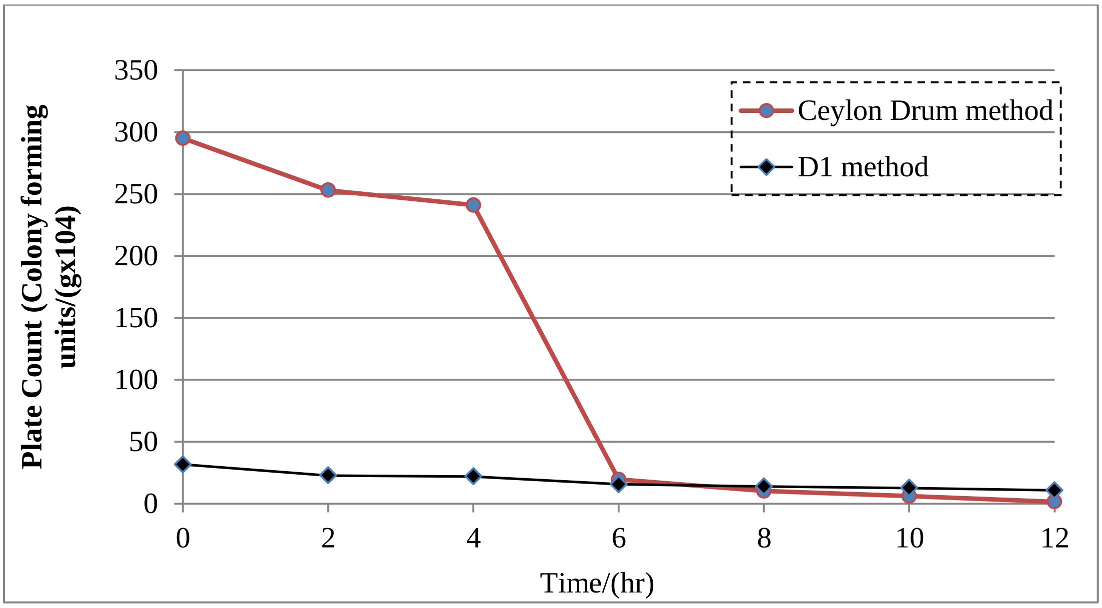

Figure 6.5: Effect of drying on the microbial behavior

Figure 6.5 suggests that sun drying is very effective in controlling the microbial levels with a very sharp drop after 4 hours. The remaining microbial content was low and had no potential threat to human health (Bhila et al., 2010). The maximum level of *Ecoli* in dried samples was found to be 20 per g which is within the limits of SLS 1991 (< 100 per g). Dried coir pith samples were also found to be free from *Salmonella*. Therefore, the coir pith obtained from both methods was suitable for making coco discs after sun drying as microbial strains were within the allowable limits.

CHAPTER SEVEN

7.0 EFFECT OF DRYING TECHNIQUE ON QUALITY OF COIR PITH

7.1 Background

Solar radiation is a cost effective heating source and widely used for drying of various vegetables, fruits and agricultural products. Although sun drying can be identified as the preferred technique for drying of coir pith due to the same reason of cost effectiveness, coir industry is now looking for alternative options to overcome the disadvantages involved with sun drying. Some are currently using hot air drying method as an alternative but most of them use flue gas at temperatures above 200 °C as the direct heating source. Consequently, the final products are not able to meet the required quality standards. Three drying techniques namely sun drying, oven drying and hot air drying were examined. Quality variations of both dried coir pith and coco discs are discussed.

7.2 Drying Behaviour of Coir Pith

Hot air drying was the most effective method of drying with the highest drying rate as compared to oven drying and sun drying (Figure 7.1). The longest time of 668 minutes to achieve moisture content of 16 - 17 % (w/w, dry basis) was recorded with sun drying. Even though same temperature of 140 °C was used for oven drying and hot air drying, the required drying time was significantly different with 160 minutes and 97 minutes respectively. As compared to oven drying, heat distribution is more uniform and also blowing air removes the moisture effectively in hot air drying.

Figure 7.1 depicts that coir pith drying process had nearly short constant rate period at the initial stage followed by a long falling rate period. During falling rate period, diffusion occurred uniformly in the sun dried coir pith due to low temperature and in hot air dried coir pith due to uniform exposure to warm air. This is in agreement with the observation of Mujaffar and Sankat (2005) on the air drying behavior of shark fillets. Oven drying showed a rapid reduction of drying rate at the final stage as compared to other methods. This may be attributed to the case hardening effect on some of the particles due to uneven heat distribution in oven drying resulting in the reduction of diffusion. Similar results were obtained by Katekawa and Silva (2007) in their study on 'drying rates in shrinking medium: Case study of banana'.

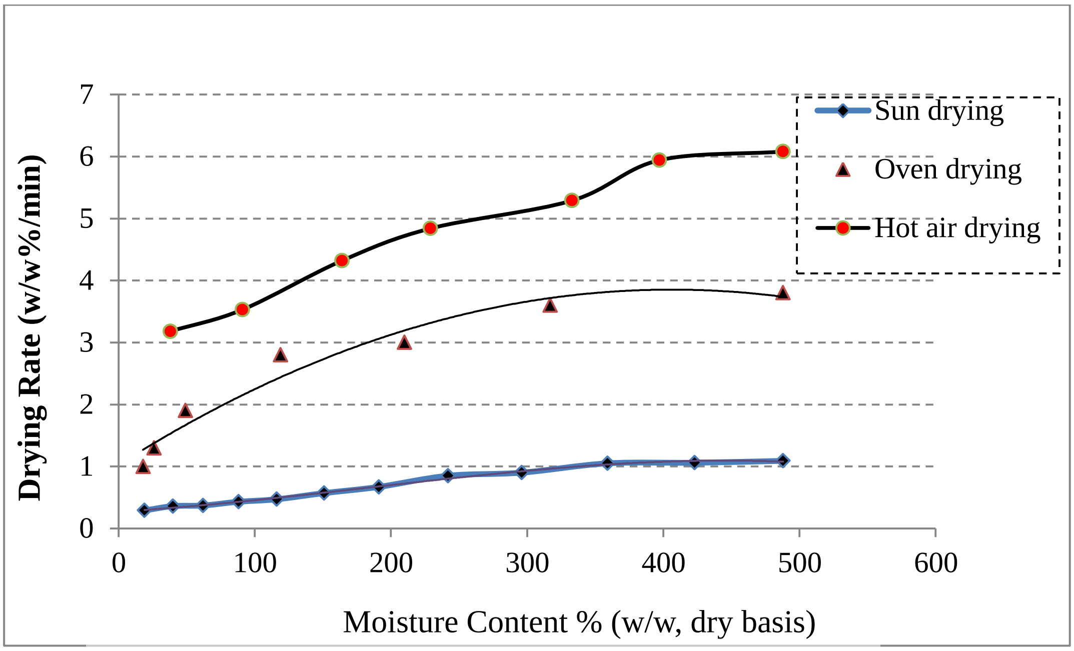

Figure 7.1: Drying rate vs moisture content of coir pith

7.3 Physicochemical properties

Table 7.1 indicates that the results of both pH and electrical conductivity of coir pith dried under sun and hot air were similar but significantly different to oven drying. SEM analysis in Figure 7.2 indicates that cells in oven dried coir pith are notably ruptured as compared to the other two methods. In oven drying, especially the particles close to surface of the aluminium tray are subjected to uneven heat transfer as compared to particles away from the surface. Uneven drying might have caused the rupturing of cells in coir pith and hence K+ ions can be easily released. Consequently pH and EC of oven dried coir pith are significantly higher than the coir pith dried under the sun and hot air. Similar results were observed by Ozcan et al. (2005) for oven drying of basil.

Table 7.1: Physicochemical properties

Sample	pH	EC(µs/cm)	VE	WRC (w/w)	BD(g//l)	CR
SD	5.92 ± 0.1[a]	542 ± 39[a]	5.33 ± 0.37[a]	6.52 ±0.14[a]	77.35 ± 2.52[a]	5.7 ± 0.49[b]
HAD	6.06 ± 0.37[a]	461 ± 77[a]	6.42 ± 0.78[b]	6.43 ± 0.43[a]	76.35 ± 1.79[a]	6.61 ± 1.04[a]
OD	6.44 ± 0.09[b]	647 ± 105[b]	5.80 ± 0.83[a]	6.03 ± 0.84[a]	83.46 ± 1.26[b]	6.53 ± 0.35[a]

Means with different superscript within the same column are significantly different from each other at $p < 0.05$ level

Coir pith is a natural material and hence expands after compaction due to resilience. This could be observed with sun dried coir pith as the coco discs were expanded notably (about 1-2 mm) soon after compression. This behavior can be called as instantaneous expansion. However, fast drying may significantly affect the resilience of coir pith. This could be observed with oven dried and hot air dried coco discs where the instantaneous expansion was not noticeable. Bulk density of coir pith is mainly affected by the particle size distribution. As explained earlier, uneven heat transfer in oven drying might have ruptured the cells in coir pith and hence the particle size distribution could be altered. This can be observed with the significantly high bulk density of oven dried coir pith as compared to the other two methods.

Compression ratio (CR) is the ratio of bulk density of coco disc to bulk density of coir pith. Bulk densities of sun dried (SD) and hot air dried (HAD) coir pith were similar but coco discs of sun dried coir pith were having considerably low bulk density due to instantaneous expansion as explained above. Therefore, CR of SD coir pith is significantly lower than that of HAD coir pith. On the other hand cells of oven dried (OD) coir pith are further ruptured during compression resulting in coco discs also having higher bulk density. Therefore, even if the oven dried coir pith was having high bulk density, CR is very similar to hot air dried coir pith.

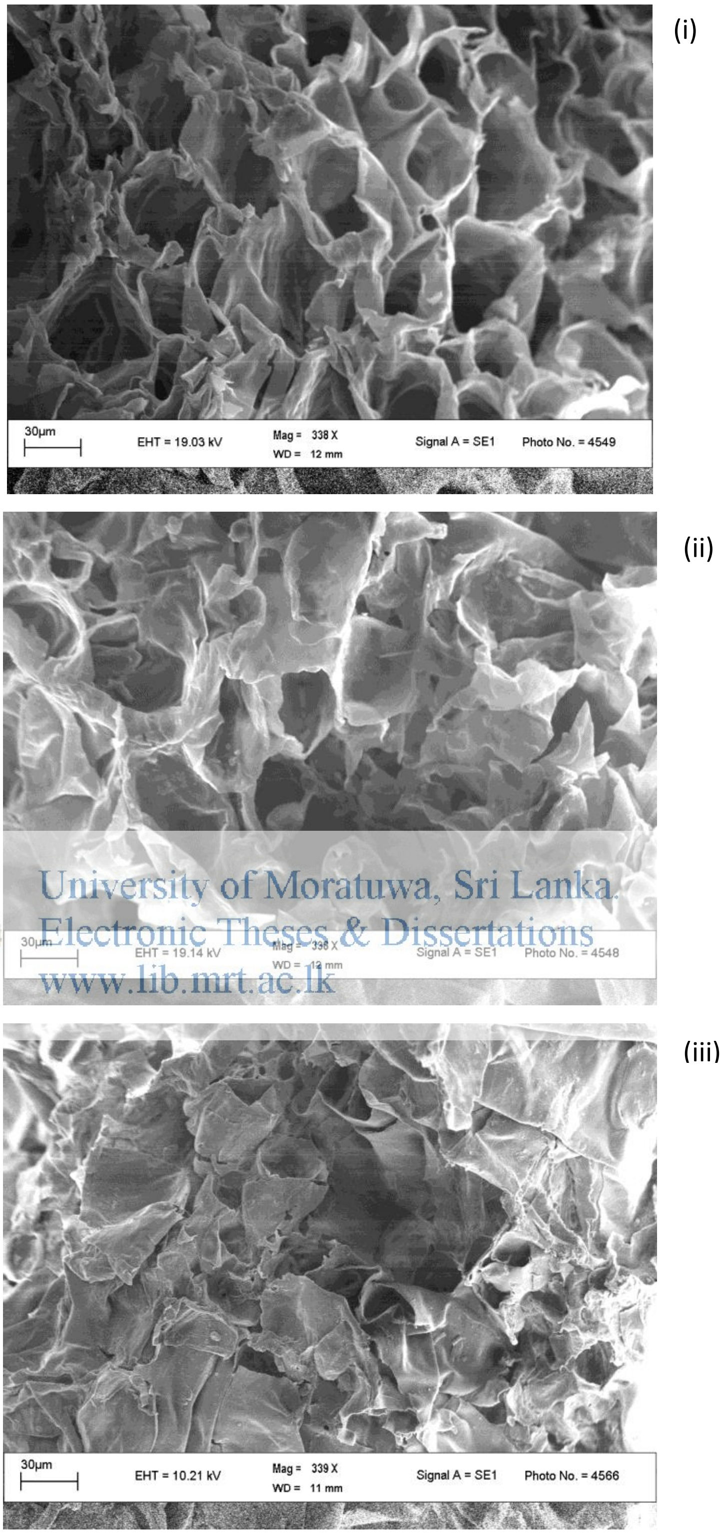

Figure 7.2: Scanning electron microstructure of (i) Sun dried (ii) Hot air dried and (iii) Oven dried coir pith

Volume expansion with the addition of water is mainly dependent on the water absorbing capacity of the cells. Therefore oven dried coir pith is having significantly low VE as compared to hot air dried coir pith due to rupture of cells. Sundried coir pith is expected to have the highest VE but Table 7.1 indicates that VE of sundried coir pith is comparable to oven dried coir pith. This may be mainly attributed to the high initial volume of coco disc of sundried coir pith due to instantaneous expansion.

7.4 Microbial Analysis of Coir Pith

Figure 7.3 depicts the reduction of microbial content of hot air, oven and sun dried coir pith. The reduction of microbial content with time is in accordance with the drying rate of different methods. The final microbial content of hot air, oven and sundried coir pith were found to be 2.16 $x10^4$, 3.56 $x10^3$ and 1.43 $x10^5$ CFU/g respectively. In each drying method *E-coli* was found to be less than 3 per 1g and *Salmonella* was totally free.

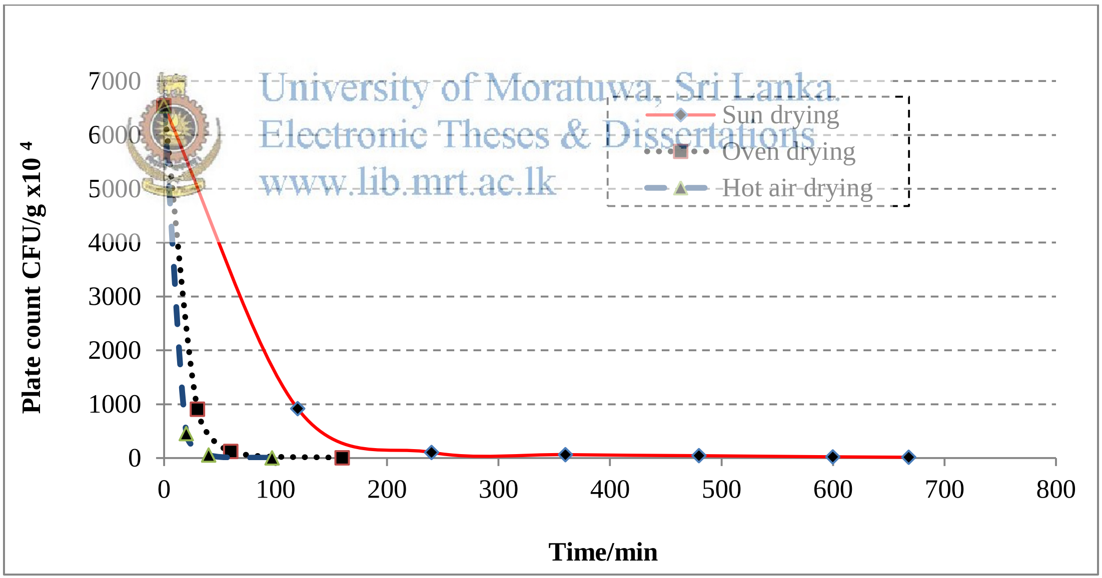

Figure 7.3: Effect of method of drying on the microbial behavior

CHAPTER EIGHT

8.0 MATHEMATICAL MODELING OF COIR PITH DRYING

8.1 Background

Drying is an essential step in processing of a porous agricultural material like coir pith. However, improper drying causes several negative effects on the structure of this biological material and the main problems can be identified as loss of rehydration ability, case hardening, color changes, shrinkage of cells, etc. Therefore examination of the drying behavior of coir pith under hot air drying technique with fluidization and circulation is highly important as it accelerates the process of drying with uniformity (Mosquera et al., 1994; Ayensu, 1997) and it gives quality products. Establishment of a proper mathematical model to describe the drying kinetics of coir pith is useful in designing of the dryer and achieving high quality coir pith products.

8.2 Results and Discussion

8.2.1 Drying characteristics

Equilibrium moisture content of coir pith for the given drying conditions of 140°C and air velocities in the range of 1.4 – 2.5 m/s was found to be 12.73 ± 0.65% (w/w, dry basis). At the beginning, coir pith was available as lumps and these lumps were found to break within the initial period of drying due to the fluidization and circulating effect. This behavior is relatively similar to particle motion and drying within a flash dryer. Free moisture is available in two forms; within the lumps and around the surface of particles. Figure 8.1 indicates that moisture content linearly reduced with time but a clear difference could be observed for the initial stage of removing free moisture and the second stage of removing the bound moisture. The drying rate corresponding to the initial period was not stable as shown in Figure 8.2. This may be mainly attributed to the combined effect of removing the retained moisture in the lumps and removing of the surface moisture of coir pith after the lumps were broken. The reduction of drying rate during the falling rate period, corresponding to the removal of bound moisture, was found to be very similar to many other agricultural and food products (Famurewa and Adejumo, 2015; Goyal et al.,2007;Togrul and Van, 2003;Vega et al.,2007).

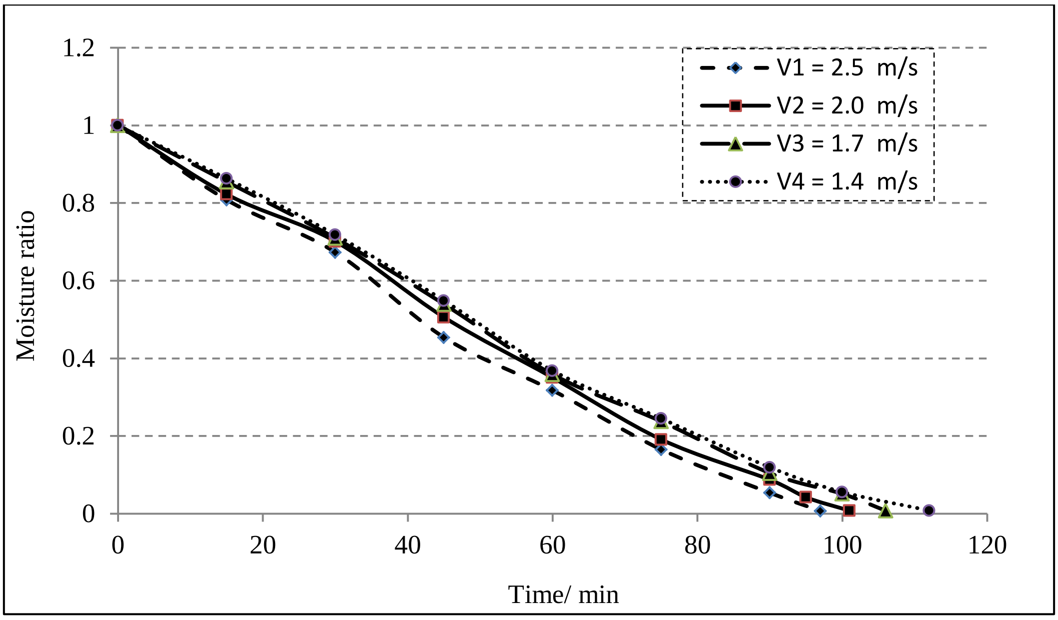

Figure 8.1: Variation of moisture ratio with time at different air velocities

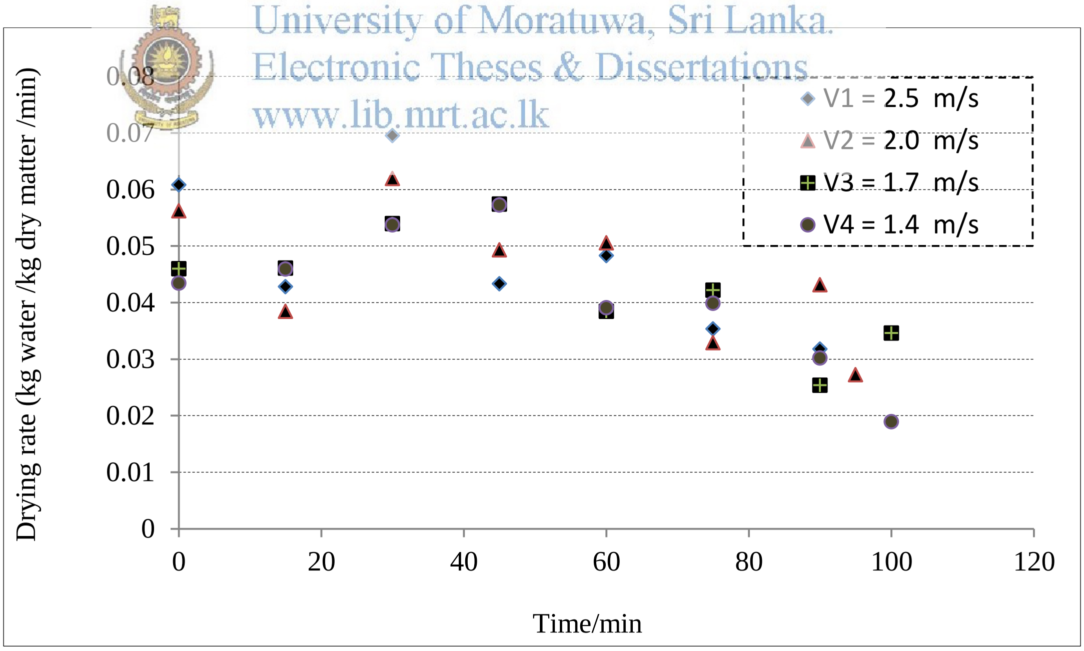

Figure 8.2: Variation of drying rate with time at different air velocities

Figure 8.2 further indicates that a significant drop in drying time could be achieved with the increase in air velocity. The drying times corresponding to the velocities of

2.5, 2.0, 1.7 and 1.4 m/s were observed as 97 ± 1, 101 ± 1, 106 ± 2 and 112 ± 2 minutes respectively. Similar trends were observed by Niamnuy and Devahastin (2005) in their study of fluidized bed drying of coconut kernel. The increase in drying rate was attributed to the increase in convective heat transfer coefficient between the product and the air (Zhu and Jiang, 2014).

8.2.2 Mathematical modeling of hot air drying of coir pith with fluidization and circulation

Thin layer drying models are useful in predicting the drying kinetics of many agricultural and food materials. However, all the exponential models (Eq. [4.2], Eq. [4.3], Eq. [4.4] and Eq. [4.5]) were failed to describe the drying behavior of coir pith using hot air. One of the reasons may be the circulation of coir pith particles within the drying chamber in addition to the fluidization. It was also noted that the equilibrium moisture content for coir pith was found to be 12.73 ± 0.65% (w/w, dry basis) which is rather a higher value compared to other agricultural materials. On the other hand, the moisture content in coir pith was reduced only up to about 16 - 17% (w/w, dry basis) in order to satisfy the secondary operation of compaction. Therefore, the final stage of slow rate of drying until reaching the equilibrium moisture content was not applicable for the coir pith. However, both Wang and Singh model and Linear model were found to have good correlations with the actual data.

Table 8.1 summarizes the results of non-linear regression analysis and the model constants for Wang and Singh model, Linear model and also the proposed new model.

According to Table 8.1, all three models confirm quality fit with R^2 values close to 1 and RMSE values close to zero. However, reduced χ^2 values for Linear model are considerably higher than the other two models. Reduced chi-square (χ^2) is the mean square of the deviations between experimental and predicted values for the models and is a primary statistical parameter used to examine the goodness of the fit. Further, a considerable increase in χ^2 value could be observed with the reduction of hot air velocity for the Wang and Singh model. A similar behavior was observed with the new model but the increase of χ^2 value is only marginal. These results suggest that the new model is the most suitable model for describing the drying kinetics of coir pith using hot air with fluidization and circulation. The percent mean relative deviation modulus (E %) further confirms it with values less than 10 for three of the hot air velocities used in this study. Comparatively other two models have significantly high E% values.

Table 8.1: Statistical results from thin layer drying models

Model	Velocity (m/s)	Model constants			R^2	Red. χ^2 $\times 10^2$	RMSE	E%
		a	B x 10^2	C x 10^2				
$MR = 1 + at + bt^2$ (Wang and Singh model)	2.5	-0.01282	0.0025525		0.9981	0.0297	0.0149	21.45
	2	-0.01174	0.001763		0.9977	0.0354	0.0175	23.95
	1.7	-0.01118	0.001589		0.9974	0.0430	0.0193	27.97
	1.4	-0.0112	0.001875		0.9959	0.0708	0.0248	54.84
$MR = a + bt$ (Linear Model)	2.5	0.968159	-1.03312		0.9931	0.1077	0.0284	82.19
	2	0.97749	-0.99589		0.9948	0.0782	0.0247	60.52
	1.7	0.98372	-0.95776		0.9938	0.0944	0.0271	69.26
	1.4	0.98068	-0.92965		0.9895	0.1585	0.0351	102.5
$MR = \frac{(1 + at + bt^2)}{(1 + ct)}$ (Proposed model)	2.5	-0.01926	0.00925	-0.73063	0.9988	0.0221	0.0111	7.26
	2	-0.01896	0.00899	-0.7923	0.9987	0.0241	0.0126	7.77
	1.7	-0.01827	0.00836	-0.7766	0.9987	0.0249	0.0128	16.15
	1.4	-0.01799	0.00810	-0.7677	0.9986	0.0291	0.0149	5.67

8.2.3 Validation of the proposed model

Model constants a, b and c were found to have correlation with the air velocity and they are given in Eq. [8.1], Eq. [8.2] and Eq. [8.3] respectively. The numerical values of all the related constants are summarized in Table 8.2.

$$a = a_1 v^2 + a_2 v + a_3 \quad [8.1]$$

$$b = b_1 v^2 + b_2 v + b_3 \quad [8.2]$$

$$a = c_1 v^2 + c_2 v + c_3 \quad [8.3]$$

Where v is the velocity of air

Table 8.2: Model constants for the proposed model

a		b		c	
a_1	0.0005433	b_1	-0.51675×10^{-5}	c_1	0.001268
a_2	-0.003347	b_2	3.13385×10^{-5}	c_2	-0.00465
a_3	-0.01431	b_3	4.67223×10^{-5}	c_3	-0.00361

Residual analysis was used to examine the validation of the proposed model. Figure 8.3 indicates that actual and predicted data have excellent correlation with R^2 value of 0.9984. The corresponding residual plot is given in Figure 8.4. Considering the overall fit, residuals are so close to the value zero and are randomly distributed, indicating the goodness of the fit (Ghaderi et al.,2012).

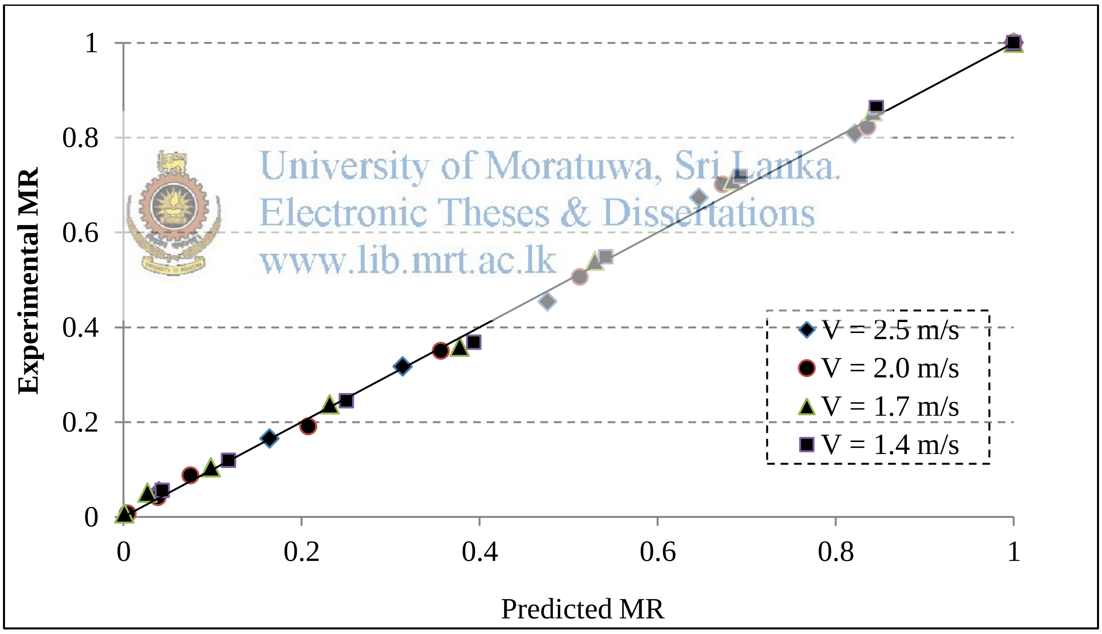

Figure 8.3: Experimental and predicted moisture ratio with proposed model at different air velocities

8.2.4 Effective moisture diffusivity

The effective moisture diffusivity was calculated using Eq. [3.6] and the values are summarized in Table 8.3. Moisture diffusivity has increased from 1.18 x10^{-8} to 1.37

x 10^{-8} (m^2/s) with the increase in air velocity from 1.4 to 2.5 m/s. Similar effect was reported in previous studies also (Arslan and Ozcan, 2010; Chen et al., 2013;Velic et al.,2004; Chayjan et al., 2011;Eterkin and Yaldiz,2004)

Table 8.3: Effect of velocity on moisture diffusivity

Velocity (m/s)	**Moisture Diffusivity** (m^2/s)
1.4	1.18×10^{-8}
1.7	1.22×10^{-8}
2.0	1.28×10^{-8}
2.5	1.37×10^{-8}

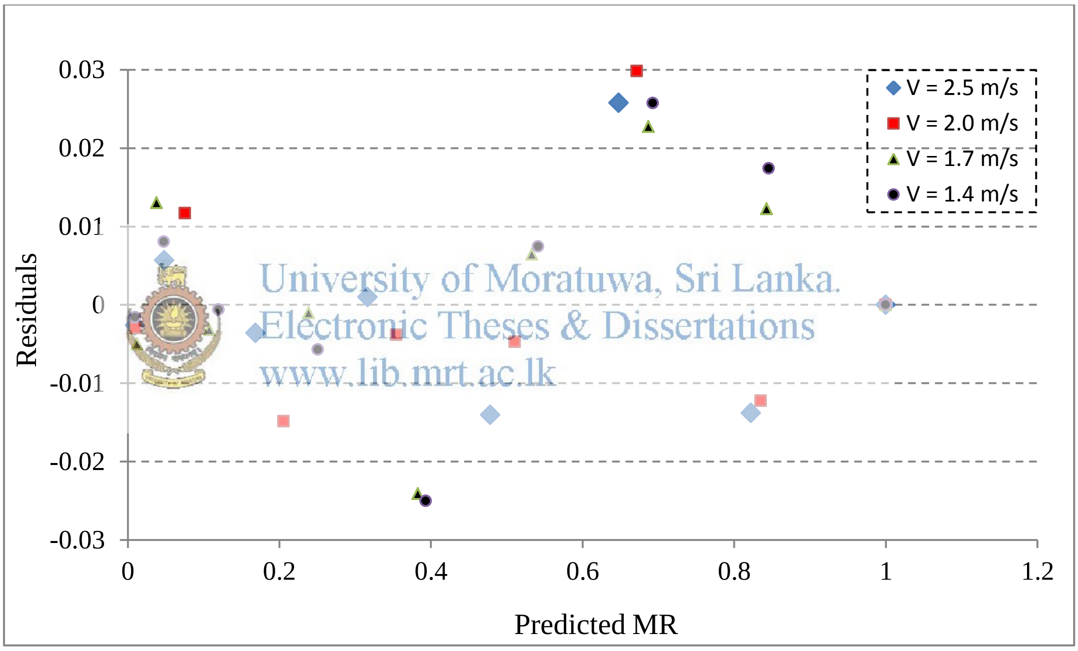

Figure 8.4: Residuals and predicted moisture ratio at different air velocities

CHAPTER NINE

9.0 FLASH DRYING OF COIR PITH

9.1 Background

Hot air drying was found to be an appropriate drying technique for coir pith drying for an alternative to sun drying. It has high performance in material drying as it involves both pneumatic conveying; high moisture evaporation due to sudden pressure reduction and high rate of heat and mass transfer. A pilot scale flash dryer was used in the present study to examine the factors influencing the flash drying of coir pith.

9.2 Results and Discussion

9.2.1 Drying characteristics of coir pith for flash drying

The average initial moisture content of the raw coir pith samples were found to be 318 ± 2% (w/w, dry basis). Figure 9.1 shows the variation of the moisture content with number of flash drying cycles for the air velocity of 32 ± 0.15 ms^{-1} and for the temperatures in the range of 120 – 160 °C to achieve moisture content in between 18 and 23% (w/w, dry basis).

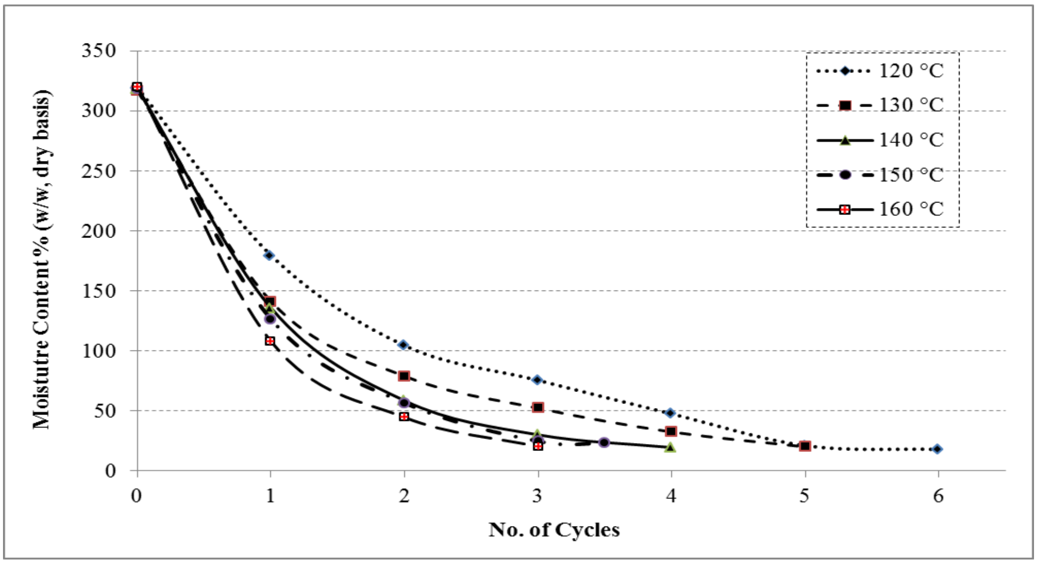

Figure 9.1: Moisture reduction with number of flash drying cycles

Moisture is available in coir pith as free moisture and bound moisture. Free moisture is available in two forms; within the lumps and around the surface of particles. The rapid reduction of moisture during the 1st cycle for drying temperatures ≥ 140 °C and the 1st and 2nd cycles for drying temperatures < 140 °C may be attributed to the removal of free moisture. The moisture reduction was found to be slow in the proceeding cycles and it may be attributed to the removal of bound moisture. In addition at initial stage, water at the surface of the product absorbs high energy leading to higher drying rate and when drying proceeds, heat transfer is decreased through the dried layer resulting in the reduction of drying rate (Arslan and Ozcan, 2010).

The optimum temperature for coir pith drying was found to be 140 °C (see section 5.2.2). The results of the flash drying experiments confirm this observation. Figure 9.1 indicates that the range of flash drying temperatures can be categorized into two main groups as < 140 °C and ≥ 140 °C. Table 9.1 indicates that the number of cycles required to reduce the moisture content from the initial moisture content of 318 ± 2% (w/w, dry basis) to the final moisture content of 18 - 23% (w/w, dry basis), was progressively decreased with increase in flash drying temperature. This may be attributed to high rate of moisture diffusion with the increase of temperature resulting in high rate of water evaporation. Similar results were observed by Tasirin et al. (2007) in their study on the drying kinetics of bird's chilies in a fluidized bed dryer and they explained the observed behavior with reference to Arrhenius Law. Table 9.1 also indicates that the number of flash drying cycles was notably reduced with increasing of air velocity. This is mainly attributed to the increase of convective heat transfer coefficient between the product and the air (Zhu and Jiang, 2014).

Table 9.1: Variation of flash drying cycles for different temperatures and velocities

Velocity (m/s)	**No. of cycles needed for drying temperatures**					**Average cycle time (min)**
	120°C	130°C	140°C	150°C	160°C	
32.0±0.15	6.0	5.0	4.0	3.5	3.0	3.00±0.07
26.1±0.20	6.5	5.5	4.5	4.0	3.5	3.37±0.06

9.2.2 Quality variations in flash dried coir pith

Although the reduction in drying time was preferred in drying process, consideration of the product quality is highly essential. Table 9.2 shows the quality variations in flash dried coir pith with reference to the drying temperature.

Table 9.2: Effect of drying temperature on quality of flash dried coir pith

Drying temperature/°C	VE	WRC(w/w)	pH	EC (μs/cm)
120	5.23 ± 0.13^{a}	4.06 ± 0.10^{ab}	5.83 ± 0.09^{a}	310 ± 6^{a}
130	5.04 ± 0.37^{a}	3.96 ± 0.11^{b}	5.94 ± 0.11^{ab}	322 ± 14^{ab}
140	5.01 ± 0.21^{a}	4.02 ± 0.10^{ab}	5.95 ± 0.08^{ab}	330 ± 16^{bc}
150	4.54 ± 0.14^{b}	3.05 ± 0.06^{c}	6.05 ± 0.08^{b}	341 ± 8^{c}
160	4.50 ± 0.13^{b}	3.40 ± 0.07^{c}	6.23 ± 0.22^{c}	375 ± 9^{d}
Sun drying (control)	5.25 ± 0.18^{a}	4.14 ± 0.09^{a}	5.97 ± 0.06^{ab}	335 ± 23^{bc}

Means with different superscript within the same column are significantly different from each other at $p<0.05$ level

ANOVA test shows that there is no significant difference in volume expansion ratio for the coco discs manufactured with flash dried coir pith at temperatures ≤ 140 °C as compared to that of sun dried coir pith but were significantly different from that of drying temperatures > 140 °C (Table 9.2). Microstructural analysis of coir pith (Figure 9.2) shows notably similar structures for flash dried coir pith at drying temperatures < 140 °C and sundried coir pith. Some of the cells were ruptured at the drying temperature of 140 °C but the bulk was still unruptured. Figure 9.2 indicates that coir pith cells got ruptured due to high drying temperatures (> 140 °C). It resulted in low volume expansion. Similar trend was also observed in WRC (Table 9.2). A notable increase in both pH and EC of coir pith was observed with increase in drying temperature. High temperatures might have ruptured the cells and the cations mainly K^+ can be easily released. Consequently high pH and EC could be observed at high temperatures. Similar results were observed by Ozcan et al. (2005) for oven drying of basil.

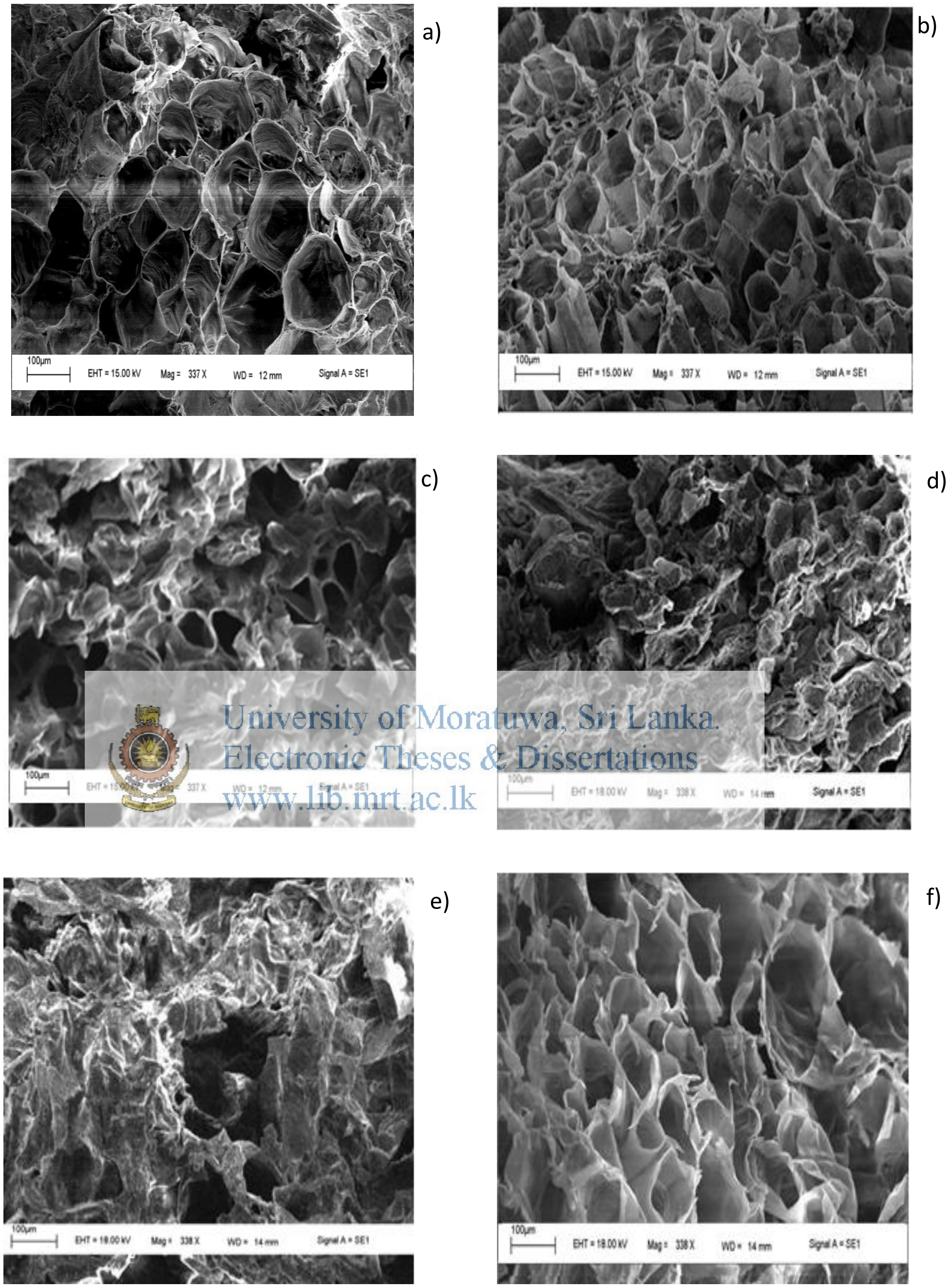

Figure 9.2: Microstructures of coir pith dried at diffent temperatures and by sun drying a) 120 °C, b) 130 °C, c) 140 °C, d) 150 °C, e) 160 °C and f) Sun drying

9.2.3 Energy analysis

The variation of SMER with respect to flash drying temperature is presented in Table 9.3. An increasing trend of SMER could be observed with increasing flash drying temperature. It could be the result of the increase of moisture diffusivity with increasing temperature. These values are within the range of SMER of hot air drying given as 0.12 - 1.28 kg/kWh (Kivevele and Huan, 2014). The increase of SMER values of coir pith dried at temperatures above 140 °C was not statistically significant. It may be attributed to the rupturing of the cell structure at high temperatures (> 140 °C) and also due to shrinkage effect.

Table 9.3: Effect of drying temperature on SMER

Drying Temperature	SMER (kg/kWh)
120 °C	0.273 ± 0.004^{d}
130 °C	0.319 ± 0.006^{c}
140 °C	0.399 ± 0.012^{b}
150 °C	0.440 ± 0.013^{a}
160 °C	0.454 ± 0.017^{a}

9.2.4 Effect of temperature on microbial count

The effect of temperature on the reduction of microbial count is presented in Figure 9.3. Flash drying technique effectively reduced the microbial count of coir pith from 4.23×10^{6} CFU/g to 4.63×10^{5}, 1.39×10^{4} and 1.80×10^{3} CFU/g at the drying temperatures of 120, 140 and 160 °C and within 5, 4 and 3 cycles, respectively. Microbial test methods also showed that *E- coli* were less than 3 per 1g of coir pith and *Salmonella* was totally free. Comparatively in the case of sun drying, reduction of microbial count from 4.23×10^{6} to 4.71×10^{5} CFU/g was observed in 9 hours.

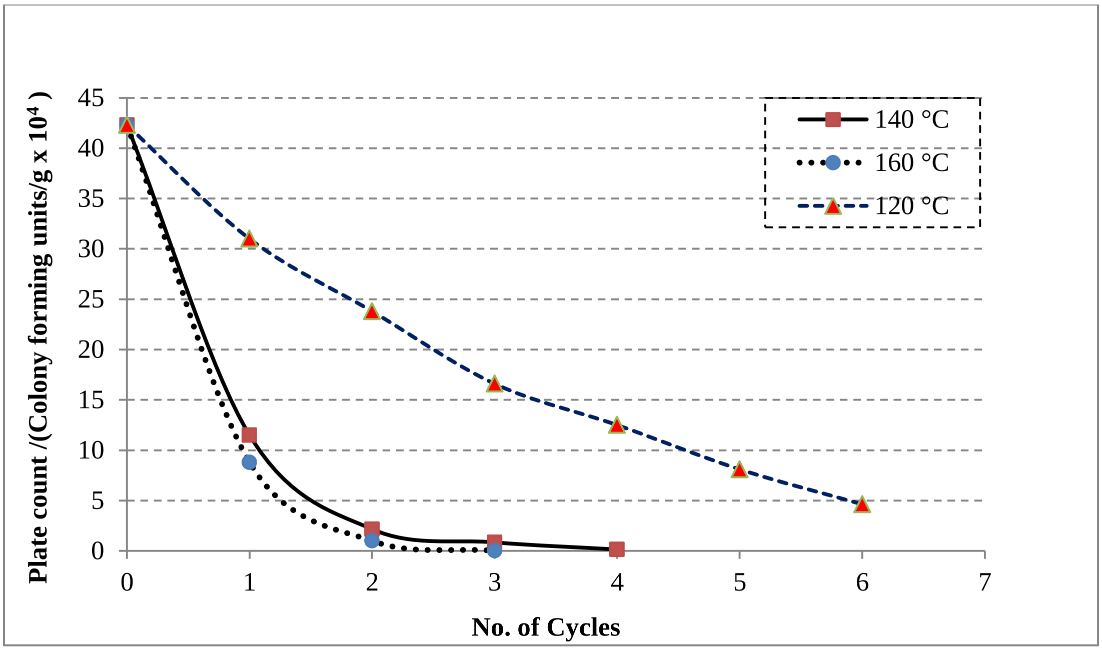

Figure 9.3: Reduction of microbial count at different flash drying temperatures

CHAPTER TEN

10.0 CONCLUSIONS

Preliminary investigation on the factors affecting the quality variations of coir pith products revealed that particles in the range of 0.5 – 6.35 mm was suitable for manufacturing compressed coir pith discs to achieve high volume expansion ratio (> 5.0). About 90% of the coir pith particles in the raw coir pith samples were found to be within this size range. Further analysis on different combinations of particles sizes confirmed that the presence of high percentage of large particles (≥ 40%) significantly affected the VE but it could be balanced by increasing the percentage of medium size particles. The results of the preliminary analysis further revealed that the optimum temperature for coir pith drying was 140 °C and the suitable moisture content was 12 – 23% (w/w, dry basis).

Volume expansion (VE) and water retention capacity (WRC) of coco discs were significantly improved with the increase of time duration for retting the coconut husks (from 4 weeks to 12 weeks). Change in pH was not significant but electrical conductivity (EC) was significantly dropped with retting time. Values of VE, WRC, pH and EC of coco discs corresponding to 12 weeks of retting period were found to be 5.77 ± 0.19, 5.87 ± 0.35, 5.99±0.04 and 63 ± 8 µs/cm, respectively. Retting facilitated the extraction of coir fiber and significantly improved the properties of fiber. Length, tensile strength and breaking load of coir fiber were found to improve from 133±1 to 182±9 mm, 81± 7 to 104± 12 N/mm^2 and 3.58± 0.42 to 4.32± 0.38 N, respectively within the time duration for retting from 4 weeks to 12 weeks. However, similar properties of coir fibre with 12 weeks of retting could be obtained for coir fibre with 4 weeks of retting, provided the husks were to crush before retting.

Retting time had a strong influence on the particle size distribution of coir pith for the two different methods of fiber extraction, namely Ceylon drum method and D1 method. For both methods longer retting time gave higher amount of fine particles (less than 1 mm) while crushing of husk before retting gave higher amount of medium size (1 - 2.8 mm) particles. However, no significant difference in physico-chemical properties of coir pith were found among mills as raw husks available for the mill operations were random in nature due to several reasons including variety of coconut husks, agro-ecological zones from where husks were collected, degree of the variation in environment conditions such as drying in sun light and exposing to rain etc. Microbial analysis revealed that the initial microbial content of raw coir pith obtained from Ceylon Drum method was about 10 times greater than that of D1 method. However, the microbial level could be effectively reduced by sun drying within 4 hours to the acceptable levels and the *Ecoli* in dried samples was found to be 20 per g which is within the limits of SLS 1991 (< 100 per g). The dried coir pith samples were also found to be free from *Salmonella.*

Hot air drying with circulation and fluidization was found to be the most effective method of coir pith drying with compared to sun drying and oven drying. The shortest drying time and the highest VE and WRC in dried coir pith were obtained in hot air drying as compared to other two methods of drying. Oven drying caused rupturing the cells and case hardening of coir pith. Consequently the pH, electrical conductivity (EC) and the bulk density of oven dried coir pith were found to be significantly higher in oven dried coir pith than the sun dried and hot air dried coir pith. Further, fast drying was found to be notably affecting the resilience property of dried coir pith. The microbial content of dried coir pith obtained from hot air, oven and sun drying were found to be 2.16 $x10^4$, 3.56 $x10^3$ and 1.43 $x10^5$ CFU/g, respectively. In each drying method *E-coli* was found to be less than 3 per 1g and *Salmonella* was totally free.

A significant drop in drying time could be achieved with the increase in hot air velocity. The drying times corresponding to the velocities of 2.5, 2.0, 1.7 and 1.4 m/s were observed as 97 ± 1, 101 ± 1, 106 ± 2 and 112 ± 2 minutes, respectively. Effective moisture diffusivity was found to increase from 1.18×10^{-8} to 1.37×10^{-8} m^2/s with the increase of air velocity from 1.4 to 2.5 m/s respectively. Typically used mathematical models for thin layer drying with exponential functions were failed to describe the drying behavior of coir pith. However, Wang and Singh model and Linear model gave good correlations. A new mathematical model was proposed and it was found to have the best correlation as compared to the other mathematical models available in literature for thin layer drying. Model constants for the proposed model were found to be quadratic functions of air velocity. Since the experimental setup of this study closely simulated the particle motion and heat and mass transfer in flash drying due to induced fluidization and circulation, the new model has a great potential in designing and modeling of the flash drying of coir pith.

Flash drying can be identified as an effective method of coir pith drying. The temperature of 140 °C was found to be the optimum temperature for flash drying considering the required number of flash drying cycles, the quality of the final product and also the specific moisture extraction rate. The quality of the final product was significantly affected by high temperatures (> 140 °C) and this may be mainly attributed to the rupturing of the cell structure which was confirmed by the analysis of scanning electron microscopy. The volume expansion, water retention capacity, pH and electrical conductivity of coir pith dried in the flash dryer at the optimum temperature of 140 °C was found to be 5.01 ± 0.21, 4.02 ± 0.10 (w/w), 5.95 ± 0.08 and 330 ± 16 μs/cm respectively. These values were comparable with those of the sundried coir pith.

Drying rate was found to be notably high during the 1st cycle for temperatures ≥ 140 °C and 1st and 2nd cycles for temperatures < 140 °C which was associated with the removal of free moisture. Subsequently the drying rate was found to be low due to removal of bound moisture. For the pilot scale flash dryer used in the current study, the minimum air velocity required to convey the particles was found to be 26.1 ms^{-1} and the cycle time could be significantly reduced by increasing the air velocity. The effective specific moisture extraction rate (SMER) could be significantly improved to 0.4 kg/kWh by increasing the drying temperature up to the optimum temperature of 140 °C. However, further increase of SMER was not significant at high temperatures (> 140 °C) may be due rupturing of the cell structure and also due to shrinkage effect.

REFERENCES

1. Abad, M., Noguera, P., Puchades, R., Maquieira, A., Noguera, V., 2002. Physico-chemical and chemical properties of some coconut coir dust for use as a peat substitute for containerized ornamental plants. Bioresources Technology, 82, 241-245.

2. Ajao, K. R., Adegun. I. k., 2009. Performance evaluation of a locally fabricated mini cassava flash dryer. Journal of Agricultural Technology, 5(2), 281-289.

3. Akpinar, E. K., Bicer, Y., Cetinkaya, F., 2006. Modeling of thin layer drying of parsley leaves in a convective dryer and under open sun. Journal of Food Engineering, 75, 308-315.

4. Akpinar, E.K., 2006. Mathematical modeling of thin layer drying process under open sun of some aromatic plants. Journal of Food Engineering, 77,864-870.

5. Arslan, D., Ozcan, M. M., 2010. Study the effect of sun, oven and micro wave drying on quality of onion slices. Journal of Food Science and Technology, 43, 1121-1127.

6. Aslaksen E. W., 2014. Mathematical model of a flash drying process. Journal of Industrial Mathematics, 2014, 1-16.

7. Ayensu, A., 1997. Dehydration of food crops using solar dryer with convective heat flow. Journal of Solar Energy,59(4-6), 121-126

8. Baeyens, J., Gauwbergen, D.V., Vinckier, I., 1995. Pneumatic drying: the use of large-scale experimental data in a design procedure. Powder Technology, 83,139-148.

9. Bhat, J.V., Nambudiri, M.D., 1972. The uniquity of coir retting, Coir, 16(4), 17-26.

10. Bhattarai, S., Kim, D. H., Oh, J., 2012. Simulation and Model validation of a pneumatic conveying drying for wood dust particles, Journal of Bio System Engineering, 37(2), 82-89.

11. Bhila, T.E., Ratsaka, M.M., Kanengoni, A., Siebrits, F.K., 2010. Effect of sun drying on microbes in non-conventional agricultural by-products. South African Journal of Animal Science. 40(5), 484-487.

12. Botheju, W.S., Amarathunge, K. S. P., Abesinghe, I.S.B., 2011. Thin layer characteristics of fresh tea leaves. Journal. of National Science. Foundation Sri Lanka, 39(1), 61-67.

13. Chayjan, R. A., Peyman, M.H., Esna-Ashari, M., Salari, K., 2011. Influence on drying conditions on diffusivity, energy and color of seedless grape after dipping process. Australian Journal of Crop Science, 5(1), 96-103.

14. Chen, D., Li, M., Zhu, X., 2013. Drying characteristics of powdered wheat straw and its mathematical modeling. Journal of Agriculture Science and technology, 15, 869-877.

15. Dan, T. K., 1993. Development of lightly weight building bricks using coconut pith, Indian Coconut Journal, 23(11), 12-19.

16. Demir, V., Gunhan, T., Yagcioglu, A. K., Degirmencioglu, A. K., 2004. Mathematical modeling and the determination of some quality parameters of air dried bay leaves. Journal of Biosystem Engineering, 88(3), 325-335.

17. Domaz, I., Ismail, O., 2011. Drying characteristics of sweet cherry, Food and Bioproducts Processing, 89, 31-38.

18. Ekechukwu, O.V., Norton, B., 1999. Review of solar energy drying systems II: an overview of solar drying technology. Energy Conservation and Management, 40, 615-655.

19. El-Behery, S., M., El-ASkary, W.A., Ibrahim, K.A., Hamed, M.H., 2011. Porous particles drying in a vertical upward pneumatic conveying dryer. International Journal of Aerospace and Mechanical Engineering, 5(2), 110-125.

20. El-Mesery, H.S., Mwithige, G., 2012. Comparison of a gas fired hot air dryer with an electrically heated hot-air dryer in terms of drying process, energy consumption and quality of dried onion slices. African Journal of Agricultural Research, 7(31), 4440-4452.

21. Erenturk, S., Gulaboglu, M. S., Gultekin, S., 2004. The thin layer drying characteristics of rosehip. Journal of Biosystem Engineering, 89(2), 159-166.

22. Ertekin,C., Yaldiz, O., 2004. Drying of eggplant and selection of a suitable thin layer drying model. Journal of Food Engineering, 63, 349-359.

23. Evens, M.R., Konduru, S., Stamps, R. H., 1996. Source Variation in Physical and Chemical Properties of Coconut Coir Dust. Horticulture Science, 31(6), 965-967.

24. Famurewa, J.A.V., Adejumo, A.O., 2015. Drying kinetics of unripe plantain chips using charcoal fuelled cabinet drye. Agric EngInt: CIGR Journal, 17(1), 227-235.

25. Farhang, A., Hosinpour, A., Darvishi, 2010. H., Accelerated Drying of Alfalfa (Medicago savita L.) by Microwave dryer. Journal of Global Veterinaria, 5(3), 158-163.

26. Garavand, A. T., Shahin, R., Keyhani, A., 2011. Mathematical modeling of thin layer drying kinetics of tomato influence of air dryer conditions, Journal of Applied Science and Technology, 2(2), 147-160.

27. Gencturk, M. b., Bakshi, A. S., Hong, Y.C., Labuza, T. P., 1986. Moisture transfer properties of wild rice. Journal of Food Process Engineering, 8(4), 243-261.

28. Ghaderi, A., Abbasi, S., Motevali, A., Minael, S., 2012. Comparison of mathematical models and artificial neural networks for prediction of drying kinetics of mushroom in microwave- vacuum drier. Chem. Industry and Chem. Eng. Quarterly, 18(2), 283-293.

29. Goyal, R. K., Kinsly, A. R. P., Manikantan, M. R., Ilyas, S. M., 2006. Thin layer drying kinetics of raw mango slices, Journal of Bio system Engineering, 95(1), 43-49.

30. Jaros, M., Pabis, S., 2006. Theoritical Models for Fluid bed drying of cut vegetables. Bio system Engineering, 93(1), 45-55.

31. Jayaseeli, D. M., Raj, S. P., 2010. Physical characteristics of coir pith as a function of its particle size to be used as soilless medium. Journal of. Agriculture. & Environment Science, 8(4), 431-437.

32. Kadalli, G.G. and Nair, S., 2000. Manurial value and efficiency of coir dust based enriched super compost, Indian coconut journal, 30(3), 49-50.

33. Kakade, S.B., Hathan, B. S., 2014. Thin layer convective dehydration kinetic of beetroot (Beta Vulgaris L.) leaves, International Journal of Innovative Research in Technology, 1,249-257.

34. Karathanos, V.T., Belessiotis, V.G., 1999. Application of a thin layer equation to drying data of fresh and semi- dried fruits, Journal of Agriculture Engineering, 74, 355-361.

35. Katekawa, M. E., Silva, M. A., 2007. Drying rates in shrinking medium: case study of banana. Brazilian Journal of Chemical Engineering, 24 (4), 561-569.

36. Kaushal, P., Sharma, H.K., 2014. Osmo-convective dehydration kinetics of jackfruit (Artocarpus heterophyllus), Journal of Saudi Society of Agricultural and Sciences, http://dx.doi.org 10.1016/. jssas ,33-41 .

37. Kivevele, T, Huan, Z. A.,2014.Review on opportunity for the development of heat pump drying system in South Africa. South. African Journal of Science, 1-11.

38. Konduru, S., Evens, M.R., Stamps, R. H., 1999. Coconut husks and processing effects on chemical and physical properties of coconut coir dust. Horticulture. Science, 34(1), 88-90.

39. Kooli, S., Fadhel, A., Farhat, A., Belghith, A., 2007. Drying of red pepper in open sun and green house conditions Mathematical modeling and experimental validation. Journal of Food Engineering, 79, 1094-1103.

40. Krishnamurthy, K.; Maheswari, C.; Udagarani, R.; Gowtham, V., 2009. Design and fabrication of coir pith briquetting machine. World applied sciences, 7(4), 552-558.

41. Limpaiboon, K., 2015. Mathematical modeling of drying kinetics of bird's eye chilies in a convective hot-air dryer, Walailak Journal of Science and Technology, 12(2), 219-227.

42. Lomauro, C. J., Bakshi, A.S., Labuza, T. P., 1985a. Evaluation of food moisture sorption isotherm equation. 1. Fruit and vegetable and meat products. Lebensmittel wisseenchaft and Technologie. 18(2), 111-117.

43. Lomauro, C. J., Bakshi, A.S., Labuza, T. P., 1985b. Moisture transfer properties of dry and semi moist foods. J. Food Sci. 50, 397-400.

44. Manikantan, M.R., Barnwal, P., Goyal, R. K., 2014. Drying characteristics of paddy in an integrated dryer, Journal of Food Science and Technology, 51(4), 813-819.

45. Manufacture of coir and coir based products, 1997. Industrial Development Board, Sri Lanka.

46. Maskan, A., Kaya, S., Maskan, M., 2002. Hot air and sun drying of grape leather (Pestil), Journal of Food Engineering, 54, 81-88.

47. Meerow, A.W., 1994. Coir (Coconut mesocarp pith) as a Peat substitute. Tropicline, 7 (3), 1-5.

48. Meisami-asl, E., Rafiee, S., Keyhani, A., Tabatabaefar, A., 2009. Mathematical modeling of moisture content of apple slices (var Golab) during drying, Pakistan Journal of Nutrition, 8(6), 804-809.

49. Menges, H. O. M., Ertekin, C., 2006.Mathematical modeling of thin layer drying of Golden apples , Journal of Food Engineering, 77, 119-125.

50. Misha, S., Mat, S., Ruslan, M.H., Sopian, K., Salleh, E., 2013.Review on the Application of a tray dryer system for Agricultural products, World Applied Science Journal, 22(3), 424-433.

51. Moorthy, V. K., Rao, K. B. 1998. Nutritive status of coir pith of varying age and from different sources. Coir News, 21 (2), 17-19.

52. Mosquera, M., Jaren-Galan, Garrido-Fernandez, J, 1994. Influence on industrial drying process on pepper fruits (Capiscum annum cv Bola) for paprika on the carotenoid content. Journal Agric. Food Chem., 42, 1190-1193.

53. Mujaffar, S., Sankat, C.K., 2005. The air drying behavior of shark fillets. Agricultural Engineering Programme, 47, 311-321.

54. Nadhari, W.N.A.W., Hashim, R., Sulaiman, O., Jumhuri, N., 2014. Drying kinetics of oil palm trunk waste in control atmosphere and open air convection drying. International Journal of Heat and Mass Transfer. 68, 14–20.

55. Narendar, R., Priya, D. K., 2012. Recent developments in coir pith based particle boards: A review, 3(2), 91-94.

56. Niamnuy, C., Devahastin, S., 2005. Drying kinetics and quality of coconut dried in a fluidized bed dryer. Journal of Food Engineering, 66, 267-271.

57. Ozcan, M., Arslan, D., Unver, A., 2005. Effect of drying methods on the mineral content of basil (Ocimum basilicum L.). Journal of Food Engineering, 69, 375-379.

58. Ozdemir, M., Devres, Y.O., 1999. The thin layer drying characteristics of hazelnuts during roasting, Journal of Food Engineering, 42, 225-233.

59. Panchariya, P.C., Popovic, D., Sharma, A.L., 2002. Thin layer modeling of black tea drying process. Journal of Food Engineering, 52(4), 349-357.

60. Prakash, S., Tha, S.K., Datta, M., 2004. Performance evaluation of blanched carrots dried by three different dryers. Journal of Food Engineering, 62, 305-313.

61. Radhakrishnan, S., Ravindranath, A. D., Hanosh, M. S., Sarma, U.S., Jayakumaran, N.A., 2012. Quantitative evaluation of the production of ligninolytic enzymes lignin peroxidase and Manganese peroxidase by P. Sajor Caju during coir pith composting, CORD, 28(1), 24-32.

62. Radhika, G.B., Satyanarayana, S.V., Rao, D.G., 2011. Mathematical model on thin layer drying of Finger Millet (*Eluesinecoracana*). Advance Journal. of Food Science and Technology, 3(2), 127-131.

63. Raquepo, M. C. M., Pabustan, C.D., Magat, S. S., 2004. Indicative nutrient supplying capacity and chemical properties of coir dust ,coco husk and other coir dust –based materials, CORD, 20(2),56-62.

64. Raveendran, K., Amarasinghe, A. D. U. S., Botheju, W. S., 2013. Drying characteristics of Orthodox broken type tea. Transactions of the institution of Engineers, Sri Lanka, 1(Part B), 432-437.

65. Ravindranath, A.D., 2001. Biotechnology in coir extraction and waste utilization. CORD, 17(2), 51-55.

66. Ross, P. R., Paramanandham, J., Thenmozhi, P., Abbiramy, K. S., Muthulingam, M., 2012. Determination of physico-chemical properties of coir pith in relation to particle size suitable for potting medium. International Journal of Research in Environmental Science and Technology, 2(2), 45-47.

67. Sarasavadia, P.N., Sawhney, R.L., Pangavhave, D.R., Singh, S.P., Drying behavior of brined onion slices, Journal of Food Engineering, 40 ,219 (1999).

68. Sarma, U.S., 2008. Value addition to coconut, Indian Coconut Journal, 51(7), 8-10.

69. Scagel, C.F., 2003. Growth and Nutrient use of Ericaceous plants grown in media amended with sphagnum moss peat or coir dust. Horticulture Science, 38(1), 46-54.

70. Skuratovsky, I., Levy, A., Borde, I., 2005.Two dimensional numerical simulation of the pneumatic drying in vertical pipes. Chemical Engineering and Processing, 44,187-192.

71. Sri Lanka Coconut Statistics, 2010, 2011, 2012, 2013, 2014, Coconut Development Authority, Sri Lanka.

72. Sri Lanka Standards Institute, 1991. Microbiological test Method, Sri Lanka Standards 516: PART 1.

73. Sri Lanka Standards Institute, 2001, Specification for coir fibre pith substrate, SLSI 1219.

74. Sutar, H., Sahoo, A., 2011. Effect of Distributor-Orifice on Drying Kinetics in a Fluidized Bed Dryer, International Journal of Chemical Engineering and Applications, 2(5), 346-351.

75. Tanaka, F., Uchino, T. Hamanaka, D., Atungula, G. G., 2008. Mathematical modeling of pneumatic drying of rice powder. Journal of Food Engineering, 88(4), 492-498.

76. Tasirin, S.M., Kamarudin, S.K., Ghani, J.A., Lee, K.F., 2007. Optimization of drying parameters of bird’s eye chili in a fluidized bed dryer, Journal of Food Engineering.80(2), 695- 705.

77. Tharanga, S. A. R., Wathulanda, H. K. P. B., Weerakkody, W. A. P., Gamlath ,S., 2005. Variation of chemical and physical properties of raw coir dust with reference to Age: Origin and extraction method. Sri Lankan Journal of Agriculture Science, 42, 01-11.

78. Tiris, C., Ozbalta, N., Tiris, M., Dincer, I., 1994. Experimental testing of a new solar dryer, International Journal of Energy Research, 18, 483-490.

79. Togrul, I. T., Pehlivan, D., 2002. Mathematical modeling of solar drying of apricots in thin layers, Journal of Food Engineering, 55, 209 -216.

80. Togrul, L. T., Van, D. P., 2003. Modeling of drying kinetics of single apricot. Journal of Food Engineering, 58(1), 23-32.

81. Vega, A., Fito, P., Andres, A., Lemus, R., 2007. Mathematical modeling of hot air drying kinetics of red bell pepper (Var Lamuyo). Journal of Food Engineering, 79(4), 1460-1466.

82. Velic, D., Planinic, M., Tomas, S., Bilic, M., 2004. Influence of air flow velocity on kinetics of convection apple drying. Journal of Food Engineering, 64, 97-102.

83. Wankhade, P.K., Sapkal, R. S., Sapkal, V.S., 2012. Drying characteristics of Okra slices using different drying methods by comparative evaluation, Proceedings of the World Congress on Engineering and Computer Science, Vol. II, October 24-26, San Francisco, USA.

84. Wilson, R.A., Kadam, D.M., Chadha, S., Sharma, M., 2012. Foam mat drying characteristics of Mango pulp, International Journal of food science and Nutrition Engineering, 2(4), 63-69.

85. Yun, T., Puspasari, I., Tasirin, S. M., Talib, M.Z. M., Daud, W.R.W., Yaakob, Z., 2014. Drying of palm frond particles in a fluidized bed dryer with inert medium, Chemical Industry & Chemical Engineering, 1994, 593-603.

86. Zhu, A., Jiang, F., 2014. Modeling of mass transfer performance of hot air drying of sweet potato, Chemical Industry & Chemical Engineering Quarterly, 20(2), 171-181.

APPENDIX

Appendix –A1 Results of quality-4 weeks retted husks

Summary Results of Coir Sample		**Report No**		**Sample Values**
Fiber Type: Bristle fiber/ 1 month				
			Results	
Date	Sp. 1	Sp. 2	Sp. 3	Final Average
1. Dimension				
1.1 Average Length, mm	133.20	134.20	132.70	133.37
Coefficient of Variation(C.V.)	0.56	0.55	0.55	0.55
1.2 Average Diameter, mm	0.25	0.23	0.24	0.24
Coefficient of Variation(C.V.)	0.25	0.22	0.28	0.25
1.3 Weighted Average Diameter	0.24	0.22	0.24	0.23
2. Fineness, g/km	59.87	54.37	55.09	56.44
3. Tensile				
3.1 Tensile Strength N/mm2	78.48	77.25	89.81	81.85
Coefficient of Variation(C.V.)	0.02	0.01	0.01	0.01
3.2. Elongation, %	24.21	26.71	26.75	25.89
Coefficient of Variation(C.V.)	0.44	0.30	0.34	0.36
3.3 Breaking Load N	3.58	3.16	4.01	3.58
Coefficient of Variation(C.V.)	0.33	0.37	0.29	0.33
**. Weighted Average				
4.1 Weighted average Breaking Load N	133.20	134.20	132.70	133.37
4.2 Weighted Average Tensile Strength N/mm^2	0.56	0.55	0.55	0.55

Appendix –A2 Results of quality-6 weeks retted husks

Summary Results of Coir Sample		**Report No**		**Sample Values**
Fiber Type: Bristle fiber/ 1.5 months				
	Results			
Date	Sp. 1	Sp. 2	Sp. 3	Final Average
1. Dimension				
1.1 Average Length, mm	137.78	134.26	137.86	136.64
Coefficient of Variation(C.V.)	55.15%	54.83%	54.19%	55%
1.2 Average Diameter, mm	0.24	0.23	0.25	0.24
Coefficient of Variation(C.V.)	25.70%	23.62%	21.00%	24%
1.3 Weighted Average Diameter	0.24	0.22	0.24	0.23
2. Fineness, g/km	54.76	54.69	51.59	53.68
3. Tensile				
3.1 Tensile Strength N/mm2	77.49	91.51	81.56	83.52
Coefficient of Variation(C.V.)	1.93%	1.37%	1.42%	2%
3.2. Elongation, %	28.52	28.70	23.99	27.07
Coefficient of Variation(C.V.)	25%	26%	34%	28.19%
3.3 Breaking Load N	3.62	3.50	3.72	3.61
Coefficient of Variation(C.V.)	41%	36%	31%	36%
**. Weighted Average				
4.1 Weighted average Breaking Load N	3.59	3.46	3.57	3.54
4.2 Weighted Average Tensile Strength N/mm^2	77.80	96.57	82.00	85.46

Appendix –A3 **Results of quality-8 weeks retted husks**

Summary Results of Coir Sample		**Report No**		**Sample Values**
Fiber Type: Bristle fiber/ 2 months				
			Results	
Date	Sp. 1	Sp. 2	Sp. 3	Final Average
1. Dimension				
1.1 Average Length, mm	164.22	134.20	129.50	142.64
Coefficient of Variation(C.V.)	0.40	0.55	0.55	0.49
1.2 Average Diameter, mm	0.23	0.23	0.24	0.23
Coefficient of Variation(C.V.)	0.30	0.24	0.27	0.27
1.3 Weighted Average Diameter	0.24	0.22	0.23	0.23
2. Fineness, g/km	54.56	54.37	49.87	52.93
3. Tensile				
3.1 Tensile Strength N/mm2	90.03	91.51	101.11	94.22
Coefficient of Variation(C.V.)	0.02	0.01	0.01	0.01
3.2. Elongation, %	26.54	28.71	23.85	26.37
Coefficient of Variation(C.V.)	0.25	0.26	0.38	0.30
3.3 Breaking Load N	3.62	3.50	4.32	3.81
Coefficient of Variation(C.V.)	0.41	0.36	0.33	0.36
**. Weighted Average				
4.1 Weighted average Breaking Load N	3.97	3.45	4.19	3.87
4.2 Weighted Average Tensile Strength N/mm^2				

Appendix –A4 **Results of quality-10 weeks retted husks**

Summary Results of Coir Sample		**Report No**		**Sample Values**
Fiber Type: Bristle fiber/ 2.5 months				
		Results		
Date	Sp. 1	Sp. 2	Sp. 3	Final
				Average
1. Dimension				
1.1 Average Length, mm	162.04	174.20	168.45	**168.22**
Coefficient of Variation(C.V.)	43.05%	36.25%	39.66%	0.39
1.2 Average Diameter, mm	0.22	0.23	0.22	0.22
Coefficient of Variation(C.V.)	25.01%	22.49%	21.29%	0.23
1.3 Weighted Average Diameter	0.23	0.23	0.23	0.23
2. Fineness, g/km	53.01	54.69	52.52	53.40
3. Tensile				
3.1 Tensile Strength N/mm2	92.88	90.47	91.41	**91.58**
Coefficient of Variation(C.V.)	1.27%	1.41%	1.36%	0.01
3.2. Elongation, %	26.36	27.93	26.76	27.01
Coefficient of Variation(C.V.)	34%	28%	32%	0.32
3.3 Breaking Load N	3.60	3.74	3.62	**3.65**
Coefficient of Variation(C.V.)	33%	34%	34%	0.33
**. Weighted Average				
4.1 Weighted average Breaking Load N	3.61	3.92	3.64	3.72
4.2 Weighted Average Tensile Strength N/mm^2	88.12	91.22	86.81	88.717

Appendix –A5 Results of quality-12 weeks retted husks

Summary Results of Coir Sample		**Report No**		**Sample Values**
Fiber Type: Bristle fiber/ 3 months				
			Results	
Date	Sp. 1	Sp. 2	Sp. 3	Final Average
1. Dimension				
1.1 Average Length, mm	175.91	192.75	178.28	182.31
Coefficient of Variation(C.V.)	0.45	0.39	0.45	0.43
1.2 Average Diameter, mm	0.25	0.21	0.22	0.22
Coefficient of Variation(C.V.)	0.18	0.24	0.25	0.22
1.3 Weighted Average Diameter	0.26	0.22	0.22	0.23
2. Fineness, g/km	61.80	70.88	61.08	64.58
3. Tensile				
3.1 Tensile Strength N/mm2	93.29	117.22	102.74	104.42
Coefficient of Variation(C.V.)	0.02	0.01	0.01	0.01
3.2. Elongation, %	31.13	32.28	30.79	31.40
Coefficient of Variation(C.V.)	0.27	0.24	0.19	0.25
3.3 Breaking Load N	4.48	3.90	3.78	4.05
Coefficient of Variation(C.V.)	0.38	0.30	0.26	0.33
**. Weighted Average				
4.1 Weighted average Breaking Load N	4.68	4.16	4.12	4.32
4.2 Weighted Average Tensile Strength N/mm^2	91.85	107.59	104.84	101.43

Appendix –A6 Results of quality-4 weeks retted husks after crushing

Summary Results of Coir Sample		**Report No**		**Sample Values**
Fiber Type: Bristle fiber/ crushed				
			Results	
Date	Sp. 1	Sp. 2	Sp. 3	Final Average
1. Dimension				
1.1 Average Length, mm	177.54	192.75	188.23	186.17
Coefficient of Variation(C.V.)	0.45	0.39	0.45	0.42
1.2 Average Diameter, mm	0.25	0.21	0.22	0.22
Coefficient of Variation(C.V.)	0.18	0.24	0.25	0.22
1.3 Weighted Average Diameter	0.26	0.22	0.22	0.23
2. Fineness, g/km	61.80	70.88	61.08	64.58
3. Tensile				
3.1 Tensile Strength N/mm2				
Coefficient of Variation(C.V.)	105.31	117.22	104.96	109.16
3.2. Elongation, %	0.02	0.01	0.01	0.01
Coefficient of Variation(C.V.)	31.13	32.28	30.79	31.40
3.3 Breaking Load N	0.27	0.24	0.19	0.25
Coefficient of Variation(C.V.)	4.48	4.01	4.21	4.23
**. Weighted Average	0.38	0.29	0.24	0.31
4.1 Weighted average Breaking Load N	4.68	4.16	4.12	4.32
4.2 Weighted Average Tensile Strength N/mm^2	91.85	107.59	104.84	101.43