

**DEVELOPMENT AND CHARACTERIZATION OF A
PARTICLEBOARD FROM COCONUT SHELL AND POTATO
WASTE FOR HOUSING CONSTRUCTION APPLICATIONS**

By

ALSADIQ ALAMIN IBRAHIM MOHAMMED

A thesis submitted in partial Fulfilment of the Requirement for the Award of the Degree
of Master Science in Industrial Engineering, Department of Manufacturing, Industrial,
and Textile Engineering, School of Engineering, Moi University- Eldoret, Kenya

April 2024

Declaration by the Candidate

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission of the author and/or Moi University.

Signature  .

April 23,2024

Alsadiq Alamin Ibrahim Mohammed

Date

ENG/MIE/4179/20

Declaration by Supervisors

This thesis has been submitted for examination with our approval as University Supervisors.

Prof. John T. Githaiga

Signature 

Date April 29,2024

Department of Manufacturing, Industrial and Textile Engineering, Moi University

P.O Box 3900-30100, Eldoret, Kenya

Dr. David Njuguna Githinji

Signature 

Date 29/04/2024

Department of Manufacturing, Industrial and Textile Engineering, Moi University

P.O Box 3900-30100, Eldoret, Kenya

DEDICATION

I dedicate this work to my family and many friends A special feeling of gratitude to my loving parents, Alamin and Fatima for their words of encouragement and pushing, my sisters, brothers, my wife and children.

ABSTRACT

Coconut shell particles (CSP), an agro-waste product of coconut (*Cocos Nucifera*), is generated in large quantities from coastal parts of Kenya and in food industries. This waste is generally disposed of in open areas adversely affecting the environment. Another agro-waste produced in large quantities and disposed of by hotels in urban areas is potato tuber waste (PTW); these have been used to prepare CSP reinforced potato tuber waste (tuber solanum) particleboard (PB). The main objective of this study was to develop a PB from CSP and PTW for housing construction applications. Specific objectives included: analysing the chemical and physical properties of raw and processed CSP, fabrication of a PB using processed CSP at varying consolidation pressure, temperature and particle sizes and evaluation of the physical and mechanical properties of the board. CSP was subjected to particle size distribution. The PB prepared by incorporating different volume fractions of water-ethanol treated CSP into PTW with 30% of water as a plasticizer. CSP of sizes of 1, 2, 3.15 and 4 mm and PTW were blended at ratios of 10:90, 20:80, 30:70, 40:60 and 50:50 % and moulded into PB using hot hydraulic compression. The manufactured boards were analysed to ascertain the effects of resin content, blend percentage, and particle size on the board's properties, and characterized for physical and mechanical properties. The lignocellulosic, moisture and ash contents of CSP from both untreated and treated samples were analysed. CSP and PTW were thermally analysed. The resulting PB were then examined using a variety of techniques, including mechanical characteristics, Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), water absorbance, and thickness swelling. For the sizes of 1, 2, 3.15, and 4 mm, the fractions of the particle sizes were distributed as 0.33, 0.32, 0.28, and 0.05, respectively. The lignin, cellulose and hemicellulose content of the untreated and treated CSP varied between 30.83% to 34.41% for lignin, 23.61% to 34.65% for cellulose and 32.53% to 30.55% for hemicellulose while the moisture content of raw CSP and CSP residue was 5.90% and 12.09%

respectively. Ash content was found to be 0.76% and 0.86 % for raw CSP and treated CSP respectively.

The results showed that the tensile strength of the treated CSP board varied from 1.10 to 8.17 MPa, the modulus of rupture of CSP particleboard varied from 7.35 to 16.20 N/mm², the water absorbance of the composites increased significantly from 21.87 to 56.98%, the thickness swelling varied from 14.76% to 52.11%, and the density laid at the range of 0.11 to 0.15 g/cm³. From the results it was concluded that the maximum weight fraction of CSP size distribution was at 1 + < 1 mm, lignin and cellulose content increased for the treated CSP while hemicellulose decreased, the optimal conditions of fabricating the board was at 10 MPa ,160 °C and 10 minutes and that physical and mechanical properties depend on the particle size, resin content and the blend percentage. Recommendation based on the findings of the study the effect of internal bonding on PB could be explored and do optimization studies on the production of PB.

Table of Contents

Declaration by the Candidate.....	II
DEDICATION.....	III
ABSTRACT.....	IV
Table of Contents.....	VI
LIST OF FIGURES	VIII
LIST OF TABLES.....	IX
ACKNOWLEDGEMENT	X
LIST OF ACRONYMS AND ABBREVIATIONS	XI
1 INTRODUCTION	1
1.1 Background of the Study	1
1.2 Statement of the Problem.....	4
1.3 Justification of the Research	5
1.4 Significance of the Study	9
1.5 Objectives of the Study.....	9
1.5.1 Main Objective.....	9
1.5.1 Specific Objectives	10
1.6 Project Methodology.....	10
1.7 Scope of the Study	10
2 LITERATURE REVIEW	12
2.1 Introduction	12
2.2 Natural Composites.....	12
2.3 Nuts Agro-wastes and Their Potential on Recycling	13
2.3.1 Biomass.....	15
2.3.2 Lignin.....	17
2.4 Use of Nut Shells in Making Composites	20
2.5 Coconut Shells.....	24
2.5.1 Coconut Shell Waste Destination	24
2.5.2 Phytochemical Extraction from Coconut Shell.....	26
2.6 Coconut Shell Composite.....	27
2.7 Composites Resin Systems.....	29
2.8 Thermoplastic Starch (TPS).....	30
2.9 Particleboard.....	31
2.9.1 Panel Manufacturing Process.....	31
2.10 Agrowaste Characterization	33
2.10.1 Moisture Content	33
2.11 Composite Production Methods	33
2.12 Characterization of Coconut Shells (CS) Composites.....	39
2.13 Characterization Techniques	40
2.13.1 Scanning Electron Microscopy (SEM)	40
2.13.2 Fourier-Transform Infrared Spectroscopy (FTIR).....	40
2.13.3 Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA)	41
2.14 Research Gap.....	41
3 MATERIALS AND METHODOLOGY	42
3.1 Introduction.....	42
3.2 Materials and Reagents	44
3.2.1 Material Collection and Preparation	44
3.2.2 Characterization of the Raw Materials	47
3.3 Methods.....	48

3.3.1	Characterization of Coconut Shells	48
3.3.2	Particleboard Fabrication	53
3.3.3	Characterization of the Particleboard.....	57
4	RESULTS AND DISCUSSION	64
4.1	Results Overview	64
4.2	Particle Size Distribution	64
4.3	Chemical and Physical Properties of Coconut Shell Particles	65
4.4	Mechanical Properties of CSP Particleboard	65
4.4.1	Tensile Strength and Modulus of Rupture	65
4.4.2	Discussion	73
4.5	Physical Properties of Fabricated Particleboard.....	73
4.5.1	Water Absorption, Thickness Swelling and Density	73
5	CONCLUSION AND RECOMMENDATIONS	91
5.1	Conclusion.....	91
5.2	Recommendations	93
5.3	Areas for Further Studies:	93
6	REFERENCES	95
7	Appendix.....	105

LIST OF FIGURES

Figure 1-1 Kenya annual production of coconut and coconut shell yield	8
Figure 1-2 Kenya annual production of potatoes tuber and potatoes peels yield	9
Figure 2-1 Hemicellulose (a), cellulose(b), and lignin (c) characteristics structures of agricultural residues (Thakur & Thakur, 2014)	18
Figure 2-2 Internal view of Coconut (Sadava et al., 2009).....	24
Figure 2-3 Coconut shell waste generation, uses and destination	25
Figure 2-4 The irreversible connection produced by thermoset cross-linking.	29
Figure 2-5 Thermoplastics connections within the chain molecules	30
Figure 2-6 Major panel manufacturing process	32
Figure 3-1 Methodological process in relation to the research objectives.....	43
Figure 3-2 Commercial grinder	45
Figure 3-3 Vibratory sieve shaker machine (Liya sieve shaker)	45
Figure 3-4 Water bath	46
Figure 3-5 Reinforcement preparation (washed, dried, ground and sorted to different sizes) ..	47
Figure 3-6 Potato tuber waste powder	47
Figure 3-7 Oven	48
Figure 3-8 Furnace.....	53
Figure 3-9 (a) Mold for forming particleboard sample (b) mold lid.....	53
Figure 3-10 A steel frame	53
Figure 3-11 Four-column hydraulic press.....	55
Figure 3-12 Coconut shell particles and potato tuber waste powder paste mixture	57
Figure 3-13 Schematic diagram for bending test on universal testing machine	61
Figure 3-14 DSC analyser.....	62
Figure 4-1 Particle size distribution of CSP	64
Figure 4-2 Tensile strength vs particle size	66
Figure 4-3 Tensile strength vs resin content	66
Figure 4-4 Modulus of rupture vs CSP size.....	67
Figure 4-5 Modulus of rupture vs resin content.....	67
Figure 4-6 Tensile strength Vs resin content and particle size	69
Figure 4-7 Modulus of rupture Vs CS particle size and resin content.....	72
Figure 4-8 Water absorption of CSPB	74
Figure 4-9 Thickness swelling of CSPB	74
Figure 4-10 CSPB density	74
Figure 4-11 SEM images of (a) pretreated CSP and (b) potato tuber waste starch (c) coconut shell particles filled potato tuber waste matrix.	81
Figure 4-12 FTIR spectrum of CSPB	84
Figure 4-13 Digital scanning calorimetry of CSP raw and residue and potato waste	85
Figure 4-14 Decomposition of the CS and MUF particleboards	87

LIST OF TABLES

Table 2-1 Chemical composition of coconut residues	26
Table 3-1 Materials used in coconut shell particleboard fabrication	44
Table 3-2 The experiment development coded table	55
Table 3-3 The experiment development uncoded table	56
Table 4-1 Coconut shell particles lignocellulosic properties	65
Table 4-2 Response 1: Tensile Strength Parallel to Surface	70
Table 4-3 Response 2: Modulus of Rupture (MOR)	72
Table 4-4 Response 3: Water Absorption	76
Table 4-5 Response 4: Thickness Swelling	78
Table 4-6 Response 5: Density ρ	80
Table 7-1 CSP particle size distribution	105
Table 7-2 Acid Insoluble Lignin (AIL) of raw CSP	105
Table 7-3 Acid soluble Lignin (ASL) of raw CSP	106
Table 7-4 Hot-water extracts solubility	106
Table 7-5 Holocellulose content of raw CSP	107
Table 7-6 Holocellulose compositions of raw coconut shell	107
Table 7-7 Acid Insoluble Lignin (AIL) of residue	108
Table 7-8 Acid Soluble Lignin of CSP residue	108
Table 7-9 Holocellulose content of CSP residue	109
Table 7-10 Holocellulose compositions of CSP residue	109
Table 7-11 Moisture content of raw CSP	110
Table 7-12 Moisture content of CSP residue	110
Table 7-13 Ash content of CSP residue	111
Table 7-14 Ash content of raw CSP	111
Table 7-15 Tensile strength Parallel to the surface (TSP) of CSP particleboard	112
Table 7-16 MOR of CSP particleboard	114
Table 7-17 Water absorption (WA) of CS particleboard	116
Table 7-18 Thickness swelling THS of CS particleboard	118
Table 7-19 Density of CS particleboard	120
Table 7-20 CSPB and MUFPB decomposition	121

ACKNOWLEDGEMENT

All praise and gratitude be to the Almighty Allah for granting me good health, strength, and guidance throughout my Master's studies. Without His blessings, this accomplishment would not have been possible. I am profoundly grateful to all the individuals and organizations who supported me during this journey. I wish to express my sincere gratitude to the Africa Centre of Excellence II in Phytochemicals, Textile & Renewable Energy (ACE II-PTRE) at Moi University, Kenya, for the scholarship that enabled me to pursue this degree.

Special thanks go to my supervisors, Prof. John Githaiga and Dr. David N. Githinji, for their steadfast support, patience, and invaluable guidance throughout my research work. I would like to express my gratitude to Moi University, particularly the School of Engineering, the MIT Lab, the Chemistry Lab, and the Civil Engineering Lab, for providing the necessary facilities for this research. My appreciation also goes to Rivatex East Africa Limited (REAL) for granting me access to their workshop and laboratory facilities, which were invaluable for completing this study.

I deeply appreciate the support of my employer, the General Commission of Industry and Investment, as well as the Ministry of Finance and Manpower, Gezira-state, for their encouragement and understanding throughout this academic endeavour. My heartfelt thanks also go to the Faculty of Industries Engineering and Technology at the University of Gezira for their academic and professional support.

Lastly, I am forever indebted to my family. To my parents, who introduced me to the value of education and instilled in me the drive to achieve my goals, I am eternally grateful. To my beloved and ever-supportive wife and children, thank you for your unwavering love, patience, and sacrifice. The time I devoted to earning this degree was time I could have spent with you, and I will always cherish your understanding and support. May Allah bless you all abundantly.

LIST OF ACRONYMS AND ABBREVIATIONS

ABBREVIATION	DEFINITION
ASTM	American Society for Testing and Materials
CSP	Coconut shell particle
CSPB	Coconut Shell Particleboard
CSPSD	Coconut Shell Particle Size Distribution
FTIR	Fourier Transform Infra-Red
TS	Tensile Strength
MOR	Modulus of Rupture
MUFPB	Melamine Urea Formaldehyde Particleboard
PB	Particleboard
PTW	Potato Tuber Waste
SEM	Scanning Electron Microscope
THS	Thickness Swelling
TSP	Tensile Strength Parallel to Surface
TAPPI	Technical Association of the Pulp and Paper Industry
TPS	Thermoplastic starch
MIT	Manufacturing, Industrial and Textile Engineering Department
WA	Water Absorption
WL	Weight Loss

1 INTRODUCTION

1.1 Background of the Study

Particleboard, a composite material derived from wood particles bonded together with adhesive and pressed under heat, finds versatile applications in furniture construction and interior design. Its manufacturing process involves the careful bonding of wood particles with a compatible adhesive, followed by thermal pressing to ensure structural integrity. Commonly utilized in crafting furniture tops, countertops, cabinets, as well as panels for flooring, walls, and ceilings, particleboard offers a cost-effective and durable solution for various architectural and design needs. Its adaptability and affordability make it a preferred choice in both residential and commercial settings, providing a sturdy foundation for visually pleasing and functional interior spaces (Wang et al., 2002), among others. Over the past five decades, there has been a significant surge in the utilization of particleboard, primarily attributed to its lightweight nature, customizable manufacturing processes in contrast to solid wood, cost-effectiveness in production, and its environmentally safer profile compared to metals and plastics. This period witnessed a notable transition in manufacturing practices, with particleboards predominantly crafted from wood chips. This evolution has revolutionized various industries, particularly in construction and furniture sectors, where the demand for versatile, sustainable materials has been steadily increasing. Particleboard's ascendancy as a preferred material owes much to its ability to meet the demands of modern design and construction, offering a balance between functionality, affordability, and environmental consciousness. (Hofstrand et al., 1984). However, availability of wood is becoming scarce due to logging, agricultural land expansion, and urbanization and population growth, thus increased demand for structural wooden products. Thus, an alternative raw material for wood in making particleboards is attractive. Therefore, presently, researches have been investigating use of agricultural residues as a

possible replacement of wood particles in manufacture of particleboards. Particles obtained from the agro-residues seems a better candidate to replace wood particles due to environmental movements, landfill regulations, recycling trends, low cost, availability, waste management and sustainability. Technically, they have cellulose, hemicellulose, and lignin same as solid particles normally used. When using agro-residue particles for making particleboards, it appears that, with proper treatment, practically some agricultural residue might be used as a particleboard source material. Many agro-residues such as cereal straws (Dai et al., 2004; Mosesson & Recycling, 1979; Zhang et al., 2003), rice husks (Vasisth & Chandramouli, 1975), groundnut shells (Jain et al., 1967) bamboo (Rowel & Norimoto, 1988), waste of tea leaves (Ors & Kalaycioglu, 1991), bagasse (Turreda, 1983), cotton, hemp and jute stalks (Kollmann, 1966), cotton stalks (Guler et al., 2002), pomace (Guerue et al., 2006), kiwi pruning (Nemli et al., 2003) flax shiv (Papadopoulos et al., 2003), vine pruning (Ntalos et al., 2002), coir pith (Viswanathan & Gothandapani, 1999), almond shell (Guerue et al., 2006), palm tree pruning (Ferrández-García et al., 2018), and apple pruning (Kowaluk et al., 2020) among others have been studied; out of the agro-wastes, use of coconut shell particles seem as a good alternative as it is classified as an agricultural biowaste; yet, when compared to glass and carbon, it can be utilized as a filler to reinforce composite materials because of its low density, low cost, eco-friendliness, thermal characteristics, high toughness, and increased biodegradability (Sahari & Sapuan, 2011; Somashekhar et al., 2018). When compared to unreinforced composites, coconut shell provides greater strength, modulus, weather resistance, and restraining capacity (Hainin et al., 2014; Somashekhar et al., 2018). The characteristics of coconut shell, are comparable to those of metal matrix composites (MMCs) (Kumar et al., 2011; Prasad et al., 2011).

Coconut (*Cocos nucifera L.*) tree is well known as the tree of life due to its many uses such as making, milk, cream, oil from the copra, the husk contains fibres used to make mats, rope, roof

thatching and baskets while the shell is utilized as an aggregate in cement, crafting and briquette (Kirti et al., 2015; Ting et al., 2016).

Hot water extraction has been shown to significantly reduce the water affinity of both softwood and hardwood, thereby improving the dimensional stability of particleboards. This process removes hemicelluloses, which enhances the compression of wood particles, increases fibre flexibility, and allows for permanent deformation, reducing spring-back effects. Consequently, particleboards made with hot water-extracted chips demonstrate improved dimensional stability and moisture resistance, making them suitable for new applications such as flooring and exterior trimming (Pelaez-Samaniego et al., 2014).

Similarly, coconut shells, which constitute about 15–20% of the coconut fruit (Lobo & Dorta, 2019; Mantia et al., 2005), present significant opportunities for sustainable particleboard production. Currently, approximately 85% of coconut shells are discarded in landfills, posing environmental and health hazards (Conroy, 2011). However, their low specific gravity (1.25) and excellent performance in reinforcing applications (Kumar et al., 2011; Shelke et al., 2014) make them ideal for particleboard manufacturing. When ground into powder, coconut shell particles (CSP) provide greater volume and exhibit excellent strength properties, which are influenced by particle size.

In addition to mechanical reinforcement, the chemical composition of CSP enhances its utility in particleboards. CSP contains hemicellulose, cellulose, and lignin, which include reactive phenolic -OH groups that boost bonding potential (Liyanage & Pieris, 2015). The presence of silica in CSP further contributes to chemical interactions between the polymer matrix and the particles, acting as a coupling agent and enhancing overall strength. These attributes underscore the potential of CSP as a sustainable and effective material for particleboard production.

And therefore, the study aims to utilize coconut shell particles to develop eco-friendly particleboard. thus, contributing in the circular economy so that the farmers and coconut oil factories can benefit from the disposed shells and mitigate the waste management problem.

1.2 Statement of the Problem

In Kenya, the primary method of solid waste disposal this involves collection and deposition in open dumpsites. Additionally, it is noteworthy that waste management responsibilities have been delegated to Councils, the local governing bodies overseeing urban areas. With urban populations on the rise, there is a corresponding increase in the volume of waste generated, placing significant strain on the limited capacity managed by local authorities.

The consequences of solid waste, particularly hazardous and non-biodegradable materials, pose significant environmental concerns that cannot be emphasized enough. As coconut oil industries mostly use coconut fruit for the coconut oil manufacturing process, the solid wastes generated from the industry contain coconut shell, which when disposed of in open landfills create adverse outcomes by producing gas emissions when burned. Coconut shell particles waste, due to its low degradability when disposed of in the environment, thus creates disposal challenges in landfills. This research aims at providing an alternative solution to waste disposal and utilization of this waste in value addition applications.

Many Kenyans rely on plastic/wood products in their day-to-day activities. However, the use of these products causes more harm to the environment and health hazards to humans and animals as well as land degradation. This is because of the non-degradable nature of these products, which make their disposal difficult.

Recently, researchers have explored the potential of replacing such items with natural fibre-reinforced composites for the fabrication of panels used in packaging (for electronics and food), automotive components, and insulation boards for construction purposes (including ceilings and partitions). Utilizing these natural fibres as reinforcements necessitates fibres that are

readily accessible and possess distinctive physical and mechanical attributes. In this research, coconut shell particles composite with better properties compared to wood, plastic, or synthetic fibre-reinforced composites was fabricated.

Particleboards made currently for furniture and interior designs are expensive due to the high cost of raw materials, thus making them unaffordable. This is due to the high cost of the conventional raw materials used in their formulation. The reliance on wood for its lignocellulose content has contributed to deforestation, prompting the search for alternative, albeit lower quality, construction materials. Incorporating crop residues into particleboard formulation offers a promising avenue to utilize alternative lignocellulose sources, which are currently disposed of primarily through open-field burning. This approach could enhance the sustainability of construction materials while addressing environmental concerns associated with deforestation and waste disposal. The use of coconut shell particles and potato wastes to formulate a reinforcement and an adhesive will result in the elimination of formaldehyde-based resins since the use of formaldehyde in particleboard formulation poses a health risk associated with oncological health hazards. Potato tuber waste is, therefore, an alternative binder for particleboard formulation. Making particleboards from these agro-wastes would introduce an alternative waste disposal method for the agro-wastes.

1.3 Justification of the Research

In the coastal areas of Kenya, families have traditionally leaned heavily on the abundance provided by coconut trees for their sustenance and financial security. Along the Kenyan shoreline, there thrive around 4.4 million coconut trees, spanning across an expansive area of approximately 44,000 hectares, a fact recorded by Mayende in 2006. A thorough examination carried out by the Agriculture and Food Authority (AFA)-Nuts/Oil Crops Directorate in the year 2015 highlighted the significant capacity that lies within the coconut industry. It revealed that this sector has the capacity to not only generate upwards of 10,000 employment

opportunities on a national scale but also significantly contribute anticipated annual revenue of KES 25 billion to the country's Gross Domestic Product (GDP).

Despite the vast potential that coconut palm cultivation presents, its spreading remains largely restricted to small-scale farms dotting the coastal regions, encompassing counties such as Kwale, Kilifi, Tana River, Lamu, Mombasa, and Taita-Taveta, rely significantly on coconut trees as vital sources of sustenance and income for their inhabitants. Mature coconuts, characterized by their distinctive thick fibrous husks encasing the well-known single-seeded nut, exhibit shapes commonly described as ovoid or ellipsoid, varying in dimensions from 300 to 450 mm in length and 150 to 200 mm in width. Shielded within their sturdy shells lie the small embryos and their abundant endosperms, comprising a combination of meat and liquid components, as extensively detailed in (Britannica, 2020; Encyclopaedia Britannica, 2021).

Moreover, the integration of coconut shell particles as effective substitutes for natural fibres in the production of eco-friendly fibre-reinforced composites has been identified as a significant advancement. Therefore, the primary thrust of current research endeavours has revolved around pioneering the development and characterization of coconut shell particle-reinforced particleboard. The inclusive objective is to harness and optimize the desirable properties intrinsic to these coconut shell particles. This entails conducting exhaustive analyses to scrutinize and compare the resultant composite properties against the backdrop of existing literature, thereby elucidating their practical applicability and potential.

Apart from the utilization of coconut shells, there is another significant waste stream that requires consideration: potato tuber waste. Often relegated to landfills where it decomposes and engenders the growth of bacteria, this waste stream presents environmental challenges. Moreover, as it decomposes, methane, a powerful greenhouse gas with substantially greater global warming potential than carbon dioxide, is released. In reaction to this, collaborative endeavours are in progress to investigate opportunities for the recycling of diverse waste

streams and their incorporation into value-added applications, thereby reducing their detrimental environmental effects. The substantial quantities of coconut shell waste generated annually, both as agrowaste and agro-industrial byproducts, necessitate proactive management strategies. With the global annual coconut production reaching a staggering 61.86 million metric tons, a substantial portion comprises coconut shells. Drawing insights from the annual coconut production in Kenya from 2016 to 2020 (Food and Agriculture Organization of The United Nations, 2020) as presented by Figure1-1, depicts the significant share of shells, accounting for approximately 15% of the whole fruit, as detailed by (Lobo & Dorta, 2019; Mantia et al., 2005) ; coconut shells are used to extract phytochemicals and colorants to be used as a natural dye, used to produce charcoal that led to an emission of carbon dioxide, 85 % of it is not used (Conroy, 2011). When these wastes are not properly disposed, they cause environmental contamination, waste management concerns and human health issues, for example a study carried out by Indeglia in 1998 for the problem of coconut shell waste in Kenya , it was projected that by the year 2048, coconut shell waste would exceed all other biodegradable waste by volume, equalling 2.5 times the quantity of all other biodegradable waste in Kenyan landfills (Indeglia, 1998) yet this issue is not exclusive to Kenya, thus takes longer time to degrade. Fortunately, the use of these wastes to produce phytochemical is on the rise. Making particleboard that are highly demanded in the modern life style due to their versatile uses from these wastes will provide an alternative solution to waste disposal as well as value addition to agrowaste. It will also allow conservation of natural resources such as wood materials. To add to these benefits, the use of these wastes will reduce environmental pollution since it contributes to the protection of forests. Production of particleboards from these wastes is ecofriendly, sustainable, and cost-effective; they contribute to the Kenyan farmer's income that will get profits from selling the shells and reduce their loss from paying to get rid of the shells.

On the other hand, Potato (*Solanum tuberosum* L.) holds a prominent position among the world's primary food crops, ranking third globally after rice and wheat in terms of both production and cultivated area (Devaux et al., 2021.) In Kenya, potatoes serve as a vital source of nutrition and livelihood for numerous families, rendering them indispensable to the population. As the third-largest producer of potatoes in Sub-Saharan Africa, Kenya significantly contributes to national food security and nutritional well-being (Muthoni et al., 2009). The production of potatoes results in the generation of considerable potato peel waste, which is a by-product of minimal value. This waste is produced in significant quantities after industrial potato processing, ranging from 15 to 40% of the initial product mass, depending on the peeling method employed, Figure 1-2 display the annual production of potato tuber and its skin (Food and Agriculture Organization of The United Nations, 2020). The utilization of food waste has garnered considerable attention within the food industry (Sepelev & Galoburda, 2015) thus the emergence of utilizing it as green binder add value to potato tuber waste.

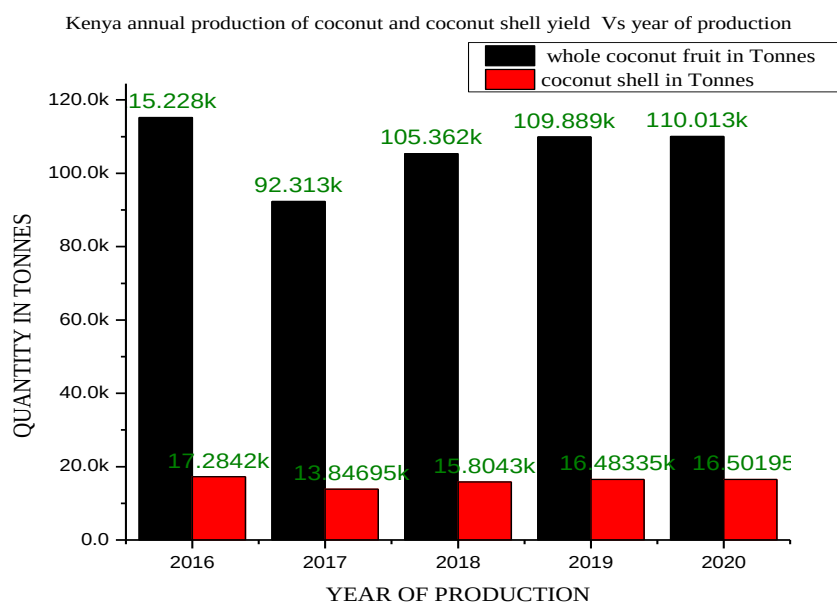


Figure 1-1 Kenya annual production of coconut and coconut shell yield

Kenya annual production of potatoes tuber and potatoes peels yield Vs year of production

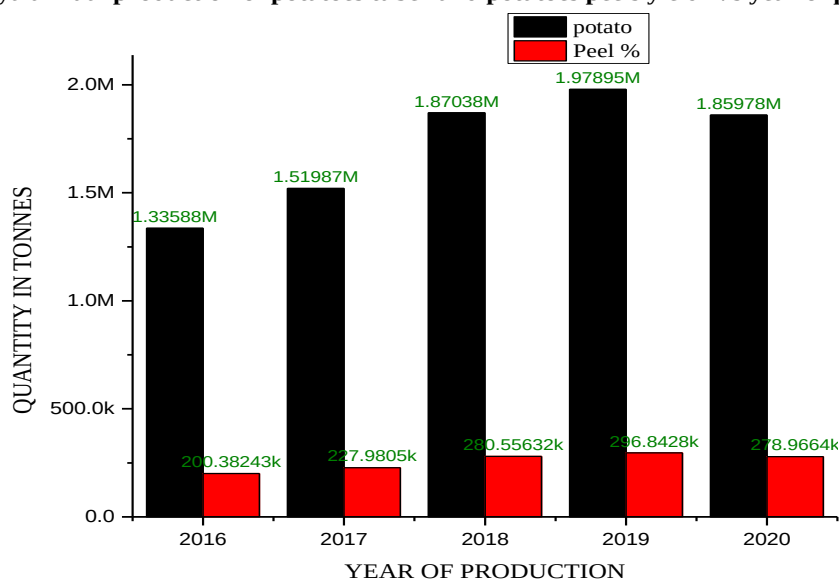


Figure 1-2 Kenya annual production of potatoes tuber and potatoes peels yield

1.4 Significance of the Study

Many problems in the agrowaste are related to pollution and expenses incurred in transportation and dumping. The use of coconut shell waste and potato tuber waste as an alternative to the wooden materials for particleboard production will minimize the amount of waste in the landfills thus reducing environmental pollution. It will provide alternative ways to manage wastes and minimize the quantity of agrowaste dumped to the environment. Utilization of these wastes on particleboard production will increase the alternative sources of raw materials for production of particleboards in Kenya and offer an employment opportunity to the people and blossom the economy of the country.

1.5 Objectives of the Study

1.5.1 Main Objective

Development and characterization of a particleboard from processed coconut shell particles (CSP) and potato tuber waste for housing construction application.

1.5.1 Specific Objectives

- I. To analyse the chemical and physical properties of raw and processed CSP for particleboard production.
- II. To fabricate a particleboard using processed CSP at varying consolidation pressure, temperature, and particle sizes.
- III. To evaluate the physical and mechanical properties of the board of the fabricated particleboard for housing construction application.

1.6 Project Methodology

This involved production of composites using a hot-press technique utilizing processed coconut shells particles as reinforcements, potato tuber waste as a resin followed by determination of mechanical and physical properties of the resultant composites.

1.7 Scope of the Study

This study focused on the development of sustainable particleboards utilizing agro-waste materials, specifically coconut shell particles (CSP) and potato tuber waste (PTW), for housing construction applications. The research aimed to evaluate the potential of these materials to address environmental and resource challenges by reducing reliance on conventional wood-based particleboards.

The study was limited to investigating the physical and mechanical properties of the particleboards fabricated under laboratory conditions. Coconut shells were sourced from the East African tall variety in Mombasa, Kenya, and PTW was procured locally in Eldoret, Kenya, as a bio-based binder. The research analysed how varying CSP particle sizes and resin blend ratios affected properties such as water absorption, thickness swelling, density, tensile strength, and modulus of rupture.

Through controlled fabrication processes and comprehensive characterization, the study sought

to identify optimal parameters and assess the suitability of these materials for practical and industrial applications.

For result analysis, Design Expert software (version 13) was employed, offering an extensive evaluation of the fabricated particleboards and their suitability for diverse applications.

2 LITERATURE REVIEW

2.1 Introduction

Wood-based panels are essential components in the construction and furniture industries, providing versatile solutions for various applications. Among the wide range of materials employed in the fabrication of panels, coconut shell particles (CSP) and potato tuber waste (PTW) have emerged as highly favourable options due to their potential to enhance sustainable production methods through resource efficiency and waste reduction. The utilization of agricultural waste materials not only addresses environmental concerns associated with waste disposal but also contributes to the development of eco-friendly construction materials. In recent years, there has been a growing interest in exploring the potential of agrowaste among nut shells and CSP as raw materials for particleboard production. Understanding the chemical and physical properties of these agricultural waste materials is crucial for optimizing manufacturing processes and enhancing the quality of particleboards. This literature review aims to provide an overview of existing research on the chemical and physical properties of CSP relevant to particleboard production. By synthesizing the findings from previous studies, this review seeks to identify key insights, gaps in knowledge, and opportunities for further research in the field of sustainable construction materials. Through analysis of the literature, this review aims to contribute to the advancement of knowledge and the development of innovative solutions for utilizing agricultural waste in particleboard manufacturing.

2.2 Natural Composites

The need for biodegradable and recyclable materials has increased due to increase in environmental awareness. As a result, natural fillers are being examined as potential substitutes for synthetic fibres in composites productions. More research is being done on developing new fillers, notably from underutilized natural resources such as peanut shell, husk and hulls (Batalla et al., 2005; Brito et al., 2022; Newton & Morrell, 2020),

macadamia nut shell (Mirindi et al., 2021; Wechsler et al., 2013), and coconut shell particles (Almeida et al., 2002; Anggraini et al., 2021; Atoyebi et al., 2021; Hatta et al., 2021; Vu et al., 2011) among others, and examining the feasibility of using them in structural and non-structural applications. The resulting bio composites are increasingly being used in industrial applications such as in aircraft, automobiles, appliances, and electrical gadgets as an outer cover. An example is panel board made from flex and microparticle with phenol formaldehyde and urethane formaldehyde as adhesives (Ismail et al., 2020). Traditionally composites have been created from fossil fuels, however due to environmental contamination caused by long-term of degradation; scientists have developed composites made from renewable materials. (Mu et al., 2018; Zheng et al., 2019). Bio-composites hold a lot of promise for solving environmental issues (Surya et al., 2020) such as deforestation, waste dumping and carbon footprint. However, due to the incompatibility between hydrophobic synthetic polymers and hydrophilic biomass, getting appropriate mechanical characteristics is difficult (Surya et al., 2020).

Nut shells are cheap agro-by product, renewable material and most of the shells go to landfills, thus utilizing the shells will add value to the agrowaste and resolve the waste management issues as well.

2.3 Nuts Agro-wastes and Their Potential on Recycling

The term "nut" is used in the culinary context to refer to a wide range of dried seeds, fruits, and any large, oily kernel found inside a shell. (Coenders, 2004). In terms of bromatology, nuts are classified as foods with an edible component that contain less than 50% weight of water, except for Brazil nuts and coconut, which contain more water than this. Nuts belong to families of the *Fabaceae* (peanut), *Rosaceae* (almond), and *Anacardiaceae* (pistachio). Among the tree nuts Almonds (*Prunus Amygdalus*), hazelnuts (*Corylus avellana L*), walnuts (*Juglans regia*), and pistachios (*Pistacia Vera*

L) are the most widely consumed. While peanuts (*Arachis hypogea*), which are technically groundnuts or legumes with a nutritional profile resembling that of tree nuts, are also included.

Nuts are seeds that have a high protein and fat content. They are frequently used as an ingredient in significant food preparations including ice cream, chocolate, confections, cookies, cereal bars, and cakes. As a snack, nuts can also be consumed raw, roasted, or salted (Zajdenweg et al., 2011). Industrial processing of nuts begins with the de-coating of the outer covering, as well as other components like leaves. The process typically generates a huge quantity of shells as the production by-product or residues the application of these agricultural leftovers has gotten much attention during last decade. However, these bio-residues are thought to include significant amounts of fibre in addition to other intriguing substances including important bioactive compounds such as flavonoids, quinones, tannins etc. (Biesaga, 2011). Mostly, due to rising energy demand, the need to minimize greenhouse gas emissions, and the potential run-out of oil supplies, nut wastes have been investigated as a potential source of a renewable energy. The coconut shell contains phytochemicals that can be used as a source of raw materials in the culinary and pharmaceutical sectors. Million tons of green coconut shells are wasted each year, which is one of the worst environmental problems (Kibria et al., 2018). Antibacterial, antioxidant, antifungal, antiviral and anti-inflammatory properties are associated with *Cocos Nucifera* and its derivatives. Due to the presence of substances like alkaloids, flavonoids, phenolic compounds, and tannins that act as antidepressants, antiparasitic, anti-diabetic, renal protective, cardioprotective, antimalarial, hepatoprotective, anti-leishmanial, anti-hypersensitivity, antineoplastic, and analgesic, it is also useful in treating physiological disorders (Lima et al., 2015). The residue that remains after the extraction of phytochemical could be used to fabricate particleboard.

2.3.1 Biomass

Biomass is the mass of living organisms such as plants, animals, and microorganisms, as well as cellulose, lignin, sugars, fats, and proteins from a biochemical standpoint. Biomass includes both above- and belowground plant tissues, such as leaves, twigs, branches, and boles, as well as tree roots and grass rhizomes. Biomass is frequently reported as a mass per unit area (i.e., m^{-2}) and is usually expressed in dry weight (water removed by drying). Unless otherwise specified, biomass typically refers to only living matter. For example, neither deadwood nor organic soil matter are considered biomass, even though soils contain biomass in the form of bacteria, fungi, and meiofauna. Soil biomass (living and dead microbes) accounts for about 5% of soil organic matter (Houghton, 2008). It is one of the most plentiful, and renewable resources on earth, which is produced by agricultural activities in the form of liquid, solid, and gaseous leftovers (Santana-Méridas et al., 2012). These byproducts are typically left in the field to rot, burned or disposed of in open landfills thus raising health and environmental concern. Forests account for 70-90 percent of terrestrial biomass, with trees accounting for most of this biomass. The global distribution of terrestrial biomass among producers, consumers, and microbes is approximately 0.90 percent, 0.001 percent, and 0.10 percent, respectively, with significant variation among ecosystems. In some non-forest ecosystems, producers and microbes, for example, may account for similar fractions of biomass (Houghton, 2008). To assure clean, sustainable environment use of these agricultural byproducts appealing. Because of this, the incorporation of agricultural wastes into various polymer matrices is encouraged to produce bio composites. These bio-composites are degradable, exhibit good strength, stiffness, and low density (Faruk et al., 2012). According to (Mande & technologies, 2005): agricultural residues can be grouped in to two main categories such as nonwoody crop residue and agro-industrial residue.

2.3.1.1 Agro Crop Biomass Residues

They are often non woody inedible plant portions that are left in the field or orchard after the primary crop has been harvested. These residues mostly consist of straw, stover, stubble, stalks, sticks, leaves, haulms, roots, branches, and twigs. Developing management methods requires a thorough understanding of the availability of agricultural residues. In spite of this, there is a shortage of complete data on the production of agricultural residues globally because it is not possible to access official or unofficial statistics sources directly. However, in many instances, it may be calculated using crop product yields and residue-to-crop ratios. (Chen et al., 2009; Lim et al., 2012)

2.3.1.2 Agro-industrial Residues or Secondary Biomass Residues

These are nonwoody byproducts obtained from the post-harvesting processing of the crop into useful products. Husks, hulls, shells peels, dust, straws, bagasse, sawdust, corncobs, pomace, and other wastes from the wood and food processing industries are some examples of these products.

The primary current uses of these residues are in the production of bio-energy due to the presence of high lignocellulosic material production, animal feed and compost, and manufacturing of industrial products, such as wood-based panels, paper, cardboard, and bio-fertilizers; among others (Santana-Méridas et al., 2012).

Higher NO, CO and SO₂ emissions for Brazil nut shells when comparing with wood pellets were reported mainly due to their higher contents of nitrogen, Sulphur, and ash; and therefore, improvements in the combustion process are required. As a result, new applications of these residues as a valuable stock material to be used in a wide range of fields have been carried out in the industry including biomaterials, compost, fertilizers, food, and feed or added value compound.

Natural fibre output reached 32 million tons in 2018, an increase of less than two million tons

over the previous ten years, (Muzyczek, 2020). These materials are primarily made of Cellulose, lignin, and hemicelluloses. They also contain small amounts of extractives, pigments, proteins, pectin, and ash can be discovered. From one plant species to another, the composition of these elements can differ. For instance, cellulose is more abundant in hardwoods, whereas hemicellulose is more prevalent in leaves and wheat straw.

Agricultural biomasses have a complex cellular structure and chemical constituents. They are essentially composite materials made of flexible lignin and hemicelluloses embedded in hard cellulose microfibrils. (Santos et al., 2002).

2.3.2 Lignin

Lignin is nature's third most abundant polymer. It is a big, complicated molecular structure made up of cross-linked polymers of phenolic monomers. It is found in plant cell walls and provides a stiff, impermeable barrier against microbial attack and oxidative stress. It is found in the primary cell wall and provides structural support, impermeability, and microbial resistance. Along with hemicellulose, lignin is a highly branched polymer that acts as a matrix to embed cellulose fibres. The intricate three-dimensional structure of lignin is made up of phenyl propane units (Figure2-1 (c)). In contrast to the linear or branching chains seen in carbohydrates, lignin connects its constituent units through a variety of carbon-carbon and ether linkages (Thakur & Thakur, 2014). It is widely regarded as the "glue" that holds the various components of lignocellulosic biomass together, rendering it insoluble in water. Lignin plays a significant role in particleboard production, primarily influencing the structural integrity and mechanical properties of the final product. As a natural adhesive, lignin contributes to the bonding between wood particles during the pressing process. Additionally, lignin provides rigidity and strength to the particleboard, enhancing its load-bearing capacity and durability (Owodunni, et al., 2020). However, excessive lignin content can also lead to challenges during board formation, such as reduced bond strength and increased resin demand. Therefore,

optimizing the lignin content is essential for achieving particleboard with desirable mechanical properties and performance (Ang et al., 2019)

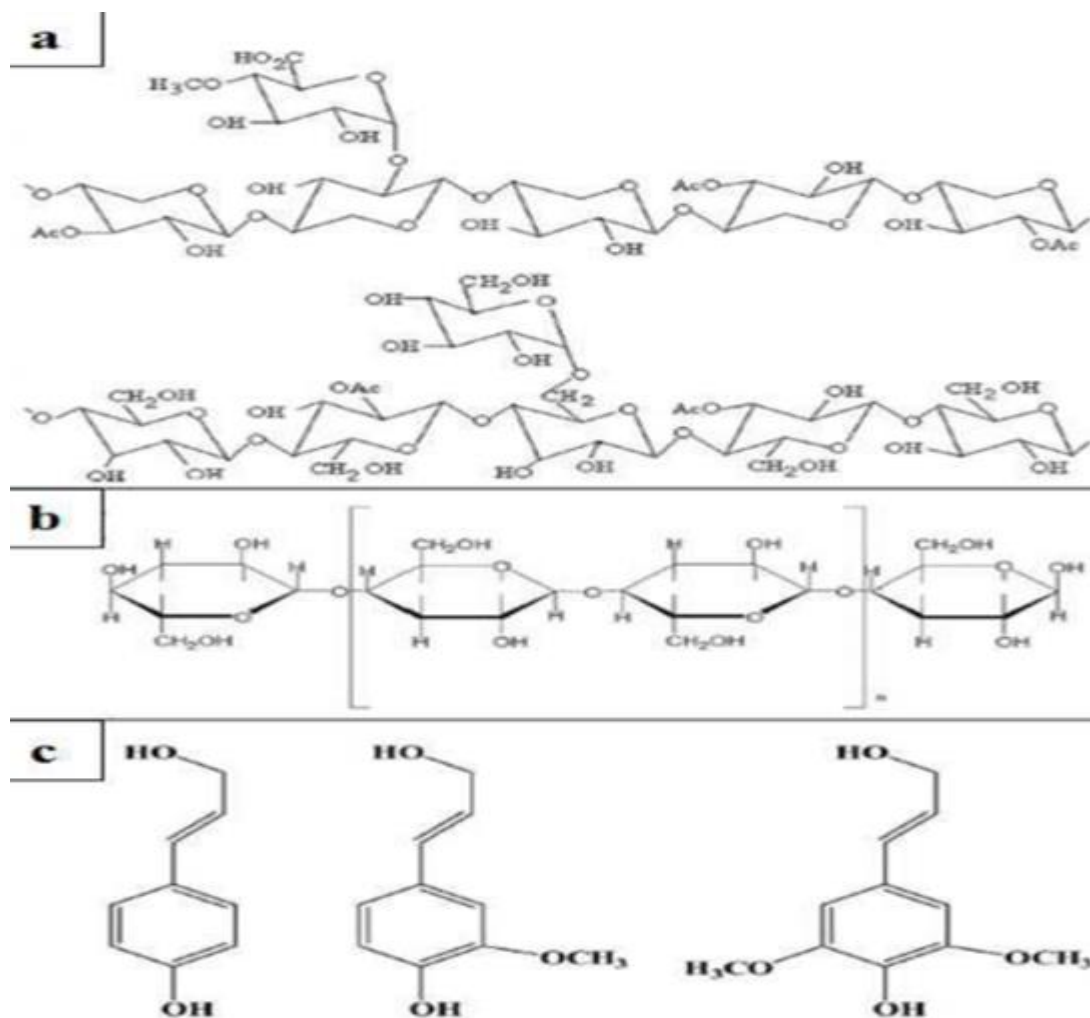


Figure 2-1 Hemicellulose (a), cellulose(b), and lignin (c) characteristics structures of agricultural residues (Thakur & Thakur, 2014)

2.3.2.1 Hemicelluloses

Hemicellulose is composed of a mixture of branching, 5- and 6-ring carbon polysaccharides (excluding pectin) that have a lower molecular weight than cellulose (Figure 2-1 (a)). The branches of hemicellulose have short lateral chains made of several kinds of carbohydrates. These monosaccharides include uronic acids, glucose, mannose, and arabinose as well as pentoses (xylose, rhamnose, and arabinose) (4-O-methylglucuronic, D-glucuronic, and D-galacturonic acids). Hemicellulose's backbone is either a homopolymer or a heteropolymer with brief branches connected by beta-(1, 4)-glycosidic links, and sporadically by beta-(1, 3)-

glycosidic linkages. Hemicelluloses can also be partially acetylated; an example of this is heteroxylan. Hemicelluloses are easier to hydrolyse than cellulose and have branches with shorter lateral chains than cellulose (Fengel & Wegener, 2011; Saha & biotechnology, 2003). Hemicelluloses are the most thermo-chemically sensitive of the lignocellulosic components (Hendriks & Zeeman, 2009; LeVan et al., 1990). In the fabrication of particleboard, hemicellulose holds significant importance, chiefly impacting the bonding and structural integrity of the end result. As a polysaccharide component of the cell wall in wood and other lignocellulosic materials, hemicellulose contributes to the adhesive properties of the particles during the manufacturing process.

During particleboard fabrication, hemicellulose acts as a natural adhesive, helping to bind the wood particles together when subjected to heat and pressure. Its presence facilitates the formation of bonds between adjacent particles, enhancing the overall strength and stability of the particleboard. Additionally, hemicellulose affects the moisture absorption and dimensional stability of particleboard.

Due to its hydrophilic characteristics, it possesses the ability to absorb and release moisture, consequently influencing the board's response to changes in humidity and temperature. Hence, comprehending the function of hemicellulose and its impacts on the manufacturing of particleboard is essential for refining production techniques and guaranteeing the excellence and functionality of the end product (Ma & Ji, 2021).

2.3.2.2 Cellulose

Cellulose is an oxygen, carbon, and hydrogen-containing complex carbohydrate. It is chiral, tasteless, and odourless discovered in 1838 by Anselme Payen, a French chemist (Reid & Dryden, 1940). It is a macromolecule having chains of varied length made up of 1–4 connected P–D–anhydro-glucopyranose units, biodegradable and water-soluble organic compound; formula $(C_6H_{10}O_5)_n$ (Figure 2-1(b)). It is the primary component of plant cell walls that

provides structural support to the plant. Cellulose is an unbranched, homopolymer with a well-recognized polymorph. From 10,000 glucopyranose units in wood to 15,000 in native cotton, cellulose chains in nature have varying degrees of polymerization. As opposed to glucose in other glucan polymers, the disaccharide cellobiose serves as the repeating unit of the cellulose chain (Desvaux, 2005; Fengel & Wegener, 2011). Microfibrils, which are bundled together to create cellulose fibres, are made up of the 20–300 cellulose chains. Van der Waals and hydrogen bonds hold the long-chain cellulose polymers together, causing the cellulose to pack into microfibrils that are protected by lignin and hemicelluloses. The "straightness" of the chain is determined by hydrogen bonding inside cellulose microfibrils, although interchain hydrogen bonds may provide order (crystalline) or disorder (amorphous) to the cellulose's structure (Laureano-Perez et al., 2005).

Cellulose serves as a fundamental element in the production of particleboard, primarily acting as the key structural component (George et al., 2023). As the most prevalent organic polymer in wood, cellulose imparts strength and stability to the particleboard (Sarı et al., 2014). Throughout the manufacturing process, cellulose fibres form a matrix that binds the wood particles together, resulting in a solid and resilient composite material. Additionally, cellulose contributes to the overall stiffness and dimensional stability of the particleboard, making it suitable for various construction and furniture applications. Moreover, cellulose is hydrophilic, meaning it has the ability to absorb and release moisture, which can influence the board's response to changes in humidity and temperature. Overall, cellulose is essential for ensuring the strength, stability, and dimensional integrity of particleboard.

2.4 Use of Nut Shells in Making Composites

Resins reinforced with natural fibres are used to make composites with specific uses. These composites are made with entirely sustainable, biodegradable, environmentally benign, and renewable fibres, notably those originating from plants.

Previous research on agricultural nut residues, such as macadamia (Dong & Davies, 2012) and walnut shells (Pirayesh et al., 2012), have reported that the use of the shells as reinforcement, increased the physical and mechanical properties of many polymer matrices. According to (Dong & Davies, 2012), shells and other debris account for over 70% of the weight of macadamia nuts. They can be burned as a wood substitute in coffee roasting, ground to produce organic waste for gardening, used as mulch in nut tree orchards, or used to make chicken litter, which is then returned to the orchard to be used as fertilizer. Macadamia nut shell is hard and brittle, having almost the same fracture toughness as conventional ceramics and glass, and it outperforms comparable materials in terms of specific strength or modulus because of its low density. The flexural characteristics of macadamia nut shell particle reinforced polyester composites (SR250 orthophthalic polyester resin) with four weight fractions of macadamia nut shell particles were investigated in this work (10, 20, 30 and 40 percent). The study of process-induced voids revealed that voids played a key role in flexural characteristics. In this regard, flexural modulus increased with macadamia nut shell particle weight fraction and reduced with increasing void content.

Because walnut shell accounts for 67 percent of the total weight of the fruit, approximately 1.8 million tons of walnut shells are left behind each year (Pirayesh et al., 2012; Santana-Méridas et al., 2012). (Pirayesh et al., 2012) investigated the suitability of walnut shell as a supplement in the production of three-layer particleboard in order to alleviate the lack of raw material in the forest industry while also reducing environmental difficulties associated with their burning. Particleboards with varied walnut shell particle ratios (0, 10, 20, 30, 40, and 100 percent) were created for this purpose using urea-formaldehyde (UF) resin. The results shown that particleboards can be made using a mixture of walnut shell and wood particles with urea-formaldehyde as a binder. To achieve the modulus of rupture guidelines, the amount of walnut shell particles in the combination should be no more than 20%. Salasinska and Ryszkowska

(Salasinska & Ryszkowska, 2017) also created a variety of composites with varying percentages of finely powdered walnut shells (10, 25, and 40% mass). The matrix was polyethylene collected via selected packaging waste collection, and the preparation procedure was divided into two stages: mixing and injection. As a result, the addition of walnut residue raised the hardness and improved the stiffness of the resultant composite significantly.

Almond shells were tested in combination with other nut residues such as walnut at various walnut/almond shell particle ratios (0, 10, 20, 30, and 100%), incorporated in a resin (Pirayesh et al., 2013), or alone as reinforcement in a thermoplastic matrix as polypropylene up to 30% particle content with and without different compatibilizers (Essabir et al., 2013). According to the findings, these leftovers can be used as alternative raw materials or fillers in the production of bio composites. In this regard, the results demonstrated a significant improvement in mechanical and rheological properties, lowering formaldehyde emissions while significantly enhancing water resistance of the panels.

Despite the outer shell, known as the hull, almonds have an inner shell called the skin. Almond skins (AS) are removed from the nut industrially by hot water blanching and account for 4-8 percent of the total shelled almond weight. Almond-processing firms are interested in monetizing these by-products, which are thought to have one of the highest fibre levels of any edible nut, as well as other intriguing components, such as flavonoids and phenolic acids with significant antioxidant activity (Mandalari et al., 2010).

As a result, incorporating low-cost AS wastes into a biodegradable polymer, such as poly (ϵ -caprolactone) (PCL), is an appealing option for converting agricultural residues into useful industrial resources that benefit the environment, energy, and economics. In fact, previously (García et al., 2014), innovative biodegradable composites based on PCL and almond skin residues were created. The addition of almond skin particles resulted in a significant improvement in mechanical characteristics, indicating the possible use of this residue as a

reinforcing agent in PCL composites. Furthermore, the presence of AS byproducts hastened the degradation of the PCL matrix in the composite films, with this effect becoming more prominent as the AS level increased. This impact was explained in terms of the polymer matrix's decreased crystallinity and the natural fibres' high hydrophilicity, which promoted water uptake and, as a result, microbial attack, and hydrolysis of the PCL matrix. Composite films with a 10% AS loading had the best performance in terms of the properties studied. Mechanical qualities were also improved as a result of good adhesion between the AS and the PCL matrix, as shown by scanning electron microscopy. When compared to plain PCL, no significant variations in thermal degradation or barrier characteristics were identified. Finally, this formulation could be an attractive environmentally friendly material to use for food packaging applications due to its biodegradable nature and increased added-value potential of almond agricultural wastes. In this respect, it is obvious that AS integration will reduce the transparency of the polymer matrix, but the resulting formulations may be ideal for the creation of sustainable food trays and similar containers where transparency is not an issue.

Caraschi, Leao, and Chamma (García et al., 2014) evaluated the use of solid residues in the preparation of panels for civil construction using peanut shell (30, 40, and 60 wt. percent). Low density panels were developed, implying that they might be used as ceilings, partitions, decorative flooring, and other applications needing similar physical and mechanical features. The architectural elements developed in this study meet the concept of an eco-efficient product made from garbage and can be used in urban or rural settings.

In conclusion, several advantages of incorporating natural fibres into biopolymer matrices are worth noting, including low density and cost, availability, recyclability, environmental friendliness, total degradation in soil without emission of toxic compounds in composting conditions, and good mechanical properties, which allow for the design of new bio composites with appropriate properties for specific applications.

2.5 Coconut Shells.

The exocarp, mesocarp, and endocarp are the three layers of the coconut fruit (Figure.2-2). The coconut husk (exocarp and mesocarp) has a variety of commercial and traditional uses. The endocarp is the hard shell with three plainly visible germination pores or eyes on its exterior surface. (AS et al., 2013). Coconut shells, the outer covering of the coconut fruit, comprise 15-20% of the nut's weight. (Lobo & Dorta, 2019; Mantia et al., 2005). The shell is made up of different weight percentage of lignin, cellulose and hemicellulose as shown in Table 2-1. Farming can offer an earning method in addition to environmental rewards and employment opportunities because to the growing global interest in utilising agrowaste residue for value-added products (Ganiron Jr & Review, 2013) The value addition process reduces waste and environmental damage.

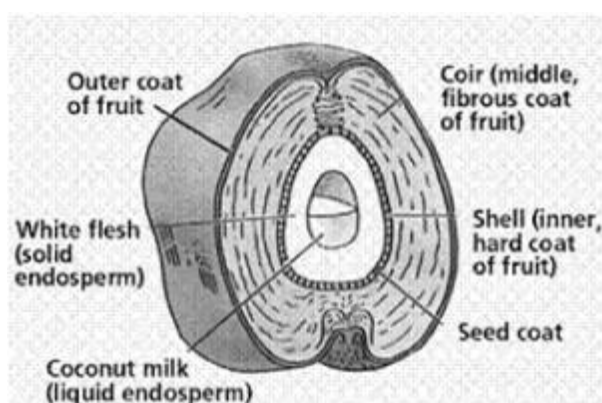


Figure 2-2 Internal view of Coconut (Sadava et al., 2009)

2.5.1 Coconut Shell Waste Destination

The generation of coconut shell waste arises from various origins, such as the food processing industries or agrowaste practices. The process of collecting and segregating the waste is conducted to eliminate any impurities or materials that are not biodegradable. A determination regarding the final disposal of the coconut shell waste is made based on its state and characteristics. Should the waste be deemed appropriate,

- **Use as fuel:** It could serve as a source of fuel for the generation of energy.

- **Composting:** One option for the utilization of coconut shell waste is through composting, which results in the production of organic fertilizer.
- **Value added products:** Moreover, the waste can undergo processing to generate products with added value, including particleboard, crafts or activated carbon. Each prospective destination leads to specific procedures or uses.

Coconut shell waste, generation, uses and final destinations are depicted in a flowchart in Figure 2–3.

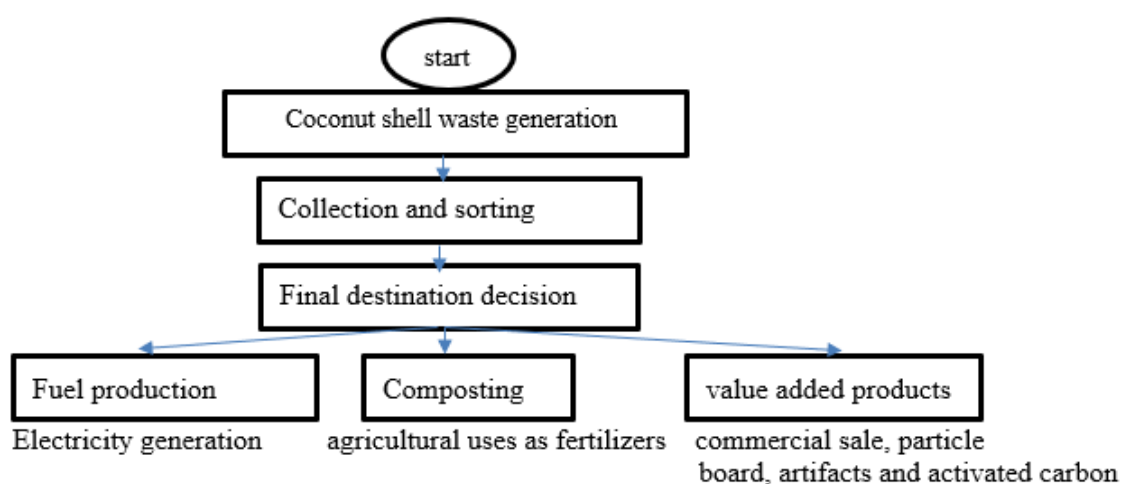


Figure 2-3 Coconut shell waste generation, uses and destination

Dumping the shells occupies a considerable area on the landfill, mulching holds water and drains well, it can moderate moisture levels and soil temperatures but on the other hand, an excessive amount of organic mulch can result in too much moisture, which can bring forth new issues including pests, anaerobic conditions, and root rot that can harm the plants (Kasirajan & Ngouajio, 2012).

Burning coconut shells negatively impacts the atmosphere by increasing the carbon footprint, while composting them is a slow process due to their long decomposition time, and utilizing them in artefacts is done on a small scale but extracting the phytochemicals and colourants for dyeing also leaves the residue as an underutilized material, which also goes to landfills; thus, utilizing it in making green composites is a good alternative as well. Coconut shell

powder is a promising contender in this regard, and, there is a lot of interest in using coconut shell particles (CSP) as a substitute for commercial fillers (Ghani et al., 2010; Liyanage & Pieris, 2015; Sareena et al., 2012). It has been used with a synthetic matrix, but using it with green resin without any chemical additives distinguishes this study.

Table 2-1 Chemical composition of coconut residues

Composition	Lignin	Cellulose	Hemicellulose	Reference
Coconut	46.0 ± 0.8	25.2 ± 1.0	27.7 ± 0.3	(Anuchi et al., 2022)
shell (wt.%)	31.04±0.10	29.58±	27.77 ±	(Gonçalves et al.,
		0.50	0.79	2019)
	18.4±0.4	32.6±0.2	23.8±1	(Zakaria et al., 2017)
	29.35	24.20	38.56	(Liyanage & Pieris,
				2015)
	36.51	33.61	29.27	(Ting et al., 2016)
	27	34	21	(Bledzki et al., 2010)
	29.4	26.6	27.7	(Salmah et al., 2013)

2.5.2 Phytochemical Extraction from Coconut Shell

Coconut shells contain various bioactive compounds, such as flavonoids, carbohydrates, reducing sugars, saponins, tannins, anthraquinones, steroids, alkaloids, glycosides, phytosterols, and phenols (Kibria et al., 2018). These compounds can serve as raw materials in industries such as culinary and pharmaceuticals. The extraction of these compounds typically involves the use of different solvents, including methanol, ethanol, acetone, and a 0.9% NaCl solution. (Kibria et al. 2018) used these solvents to isolate compounds that can act as coloring agents, antioxidants, stabilizers, foaming agents, gelling agents, and antimicrobial agents, which can help prolong the shelf life of food products. However, the residues left after extraction pose environmental challenges. These residues can be either discarded into landfills

or water resources, which may pose a potential hazard to soil microorganisms and aquatic life. Alternatively, they could be used as fertilizers or as reinforcements in board manufacturing. Each year, millions of tons of green coconut shells are wasted, contributing significantly to environmental concerns. The extracted phytochemicals from coconut shells, when properly utilized, offer a sustainable solution to this waste, providing valuable raw materials for various industries including particleboard fabrication.

2.6 Coconut Shell Composite

A coconut shell composite refers to a material crafted by blending coconut shell particles or fibres with a binding agent, typically a polymer resin. The fusion of coconut shell particles or fibres with a binding agent, typically a polymer resin, leads to the creation of a novel material with enhanced properties compared to its constituent parts. Coconut shells, abundant agricultural byproducts, are repurposed in this process, offering a sustainable solution to waste management and resource utilization challenges.

The significance of coconut shell composites extends beyond mere material innovation. Firstly, they signify a shift towards environmentally friendly approaches to manufacturing and construction industries through the utilization of coconut shells that would otherwise be disposed of as waste, these composites play a role in alleviating the environmental impact linked to agricultural by-products. Moreover, they offer an alternative to traditional materials derived from fossil fuels, aligning with the global push towards renewable resources and eco-friendly solutions.

Furthermore, the unique characteristics of coconut shell (CS) composites make them versatile and desirable for various applications (Prakash et al., 2021). Their inherent lightweight nature, coupled with respectable mechanical strength and durability, renders them suitable for applications in construction, automotive, packaging, and beyond. Additionally, their biodegradability offers an advantage over synthetic materials, particularly in environmentally

sensitive applications where disposal is a concern.

In essence, coconut shell composites symbolize the convergence of sustainability, innovation, and practicality. By harnessing the potential of agricultural waste streams, they exemplify a circular economy approach, wherein waste materials are transformed into valuable resources. As research and development efforts continue to expand in this field, coconut shell composites are poised to play an increasingly prominent role in the quest for greener, more sustainable materials.

Some research has been conducted on the use of thermosetting polymers, such as epoxy. According to (Salleh et al., 2013), demonstrating an increasing strength with increasing epoxy content in the composite. This demonstrated the suitability of CSP composites for use in lightweight applications. (Dholakiya, 2012) shows that the addition of CSP as a filler to unsaturated polyester and polyester composites the tensile strength achieved for CSP reinforced composites is in the range of 26–70 MPa which leads to increased mechanical properties, and such composites may be suitable for producing materials for domestic application (Islam et al., 2017).

Research has been carried out on CSP used as filler in low-density polyethylene composites. Different fibre lengths of the filler were used, and the highest strength value reached 7.1 MN/mm². (Madakson et al., 2012) The addition of 10 mm fibre length filler resulted in a decrease in tensile strength, but when adding the filler with 20 and 30 mm fibre length, the tensile strength increased again.

In addition, CSP was used as reinforcement in ceramic matrix composites. CSP and coarse aggregate (CA) were compared by researchers. In terms of compressive strength, based on the findings, the blended CSP with conventional aggregate produced a result that is nearly identical to the 100 percent coarse aggregate. The blended CA and CSP appeared slightly different from the conventional concrete during the 28-day testing period, demonstrating that

the blended CA and CSP can replace the use of coarse aggregate. Each of the mix proportions experienced an increase in compressive strength from day 7 to day 28 (Shambharkar et al., 2018)

Coconut fibres were used to make particleboards (*Cocos nucifera*). The panels were created with various green adhesives, including native potato starch, citric acid, and glutardialdehyde modified potato starch, which were applied at 10%, 12%, and 15% based on oven-dry particle weight for each green adhesive type. The panel's properties were determined using a Japanese industrial standard. The results revealed that the panels bonded with the 15% citric acid-modified starch green adhesive had the best mechanical properties (the modulus of elasticity, modulus of rupture, and internal bonding strength). The modified potato starch had the potential to be used as a green adhesive in the production of particleboards made from coconut fibres. (Owodunni, Lamaming, et al., 2020).

2.7 Composites Resin Systems

Resin is another crucial component in composite manufacturing that forms a matrix in the resultant structure. Polymer matrix connects the reinforcing fibres and fabrics together and serve as sizing, load distribution, and vibration dampeners in composite structure. In polymer composites, a wide range of thermoset and thermoplastic resins are employed (Ambrosio et al., 2016).

Thermosets are polymeric resins that become considerably infusible and insoluble when cured thermally, chemically (with a catalyst or promoter), and cannot be reversed, they are most widely used resins in composite material (Ramakrishnan et al., 2022). Figure 2-4 depicts the irreversible connections formed in thermosets via crosslinks.

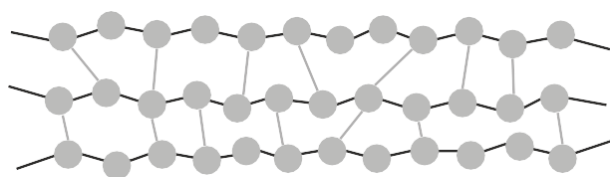


Figure 2-4 The irreversible connection produced by thermoset cross-linking.

Thermoplastics can be reheated beyond the temperature at which they were molded, making them more tolerant than crosslinking thermosets, which stiffens but loses flexibility when cooled. Although thermoplastic matrices are less expensive, they have a lower processing temperature and a narrow temperature range. Figure 2-5 depicts the strong connections within the chain molecules as well as their interactions. (Ramakrishnan et al., 2022). However, due to their high viscosity, they might pose processing challenges for composites manufacturers. The aerospace applications of thermoplastic composites reinforced with higher performance resin matrices are gaining popularity.

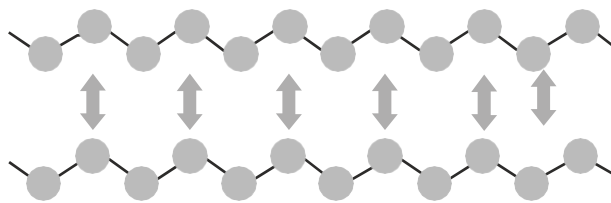


Figure 2-5 Thermoplastics connections within the chain molecules

In the production of composites unsaturated polyesters, epoxies, and vinyl esters are normally used, while polyurethanes and phenolics are rarely used (Bagherpour, 2012).

2.8 Thermoplastic Starch (TPS)

Thermoplastic starch (TPS) is a biopolymer created from native starch following the modification of its granular structure with a plasticizer such as (water, glycerol, or sorbitol, among others) (Mina et al., 2009). Water is more effective as a plasticizer than glycerol, however, because of its high boiling point, availability, and low cost, glycerol is commonly employed as a plasticizer in TPS production (Kaseem et al., 2012) TPS is made when starch granules are heated and plasticized with plasticizers, a continuous viscous phase forms that may be processed using conventional plastic processing methods such as compression molding, injection molding and extrusion (Mina et al., 2009). TPS-polymer blends were created in an effort to create new materials with low cost and great biodegradability it has been utilized as a resin in nut shell as walnut shell flour composite according to (Sarsari et al., 2016) where TPS

accelerated composite biodegradation. The thermoplastic matrices are heated in most production processes, then formed by molding, injection, extrusion, or thermoforming before being cooled to ensure the end product preserves its shape.

2.9 Particleboard

If the matrix is a polymeric substance and the dispersion phase is wood, the composite is known as wood composite, wood-based panel, wood-based board, or engineered wood. In this situation, the polymer is typically thermoset (though few tests using thermoplastics have been published), and the wood/polymer ratio ranges from roughly 80/20 to 90/10. Such composites are created by combining the materials and then heating the mixture under pressure for a set period. Wood can take the form of sheets (veneers), fibres, or particles in a variety of sizes. If veneers are used to make panels, the finished product is known as plywood. Plywood panels are formed of an odd number of veneers (plies) connected at right angles with an adhesive. When fibres are employed, the panels are referred to as fibreboards and can be low, medium, or high density. When particles are utilized to make panels, the finished product is commonly referred to as particleboard. Particleboards are classified into several categories based on their particle size, such as chipboards when using chips, flakeboards when using flakes. In this study, the terms particleboard and composite will be used interchangeably.

2.9.1 Panel Manufacturing Process

The process steps involved in panel manufacturing, starting from the storage of raw materials to the storage of the final product, occur within the wood-based panel facility. The production process of these panels is intricately connected, encompassing essential stages such as preparation, drying, and pressing. The efficiency of the overall production relies heavily on the proper execution of each intermediary step. To streamline operations, the production process is segmented into distinct phases (BAT, 2016):

- I. Raw materials preparation (receiving and sorting of particles).
- II. Drying and refining of wood particles and resin.
- III. Blending of the reinforcement and the matrix.
- IV. Formation of mats and pressing.
- V. Cooling and final finishing procedures.

In all situations, the panel manufacturing process contains the following major processes as depicted in Figure 2-6.

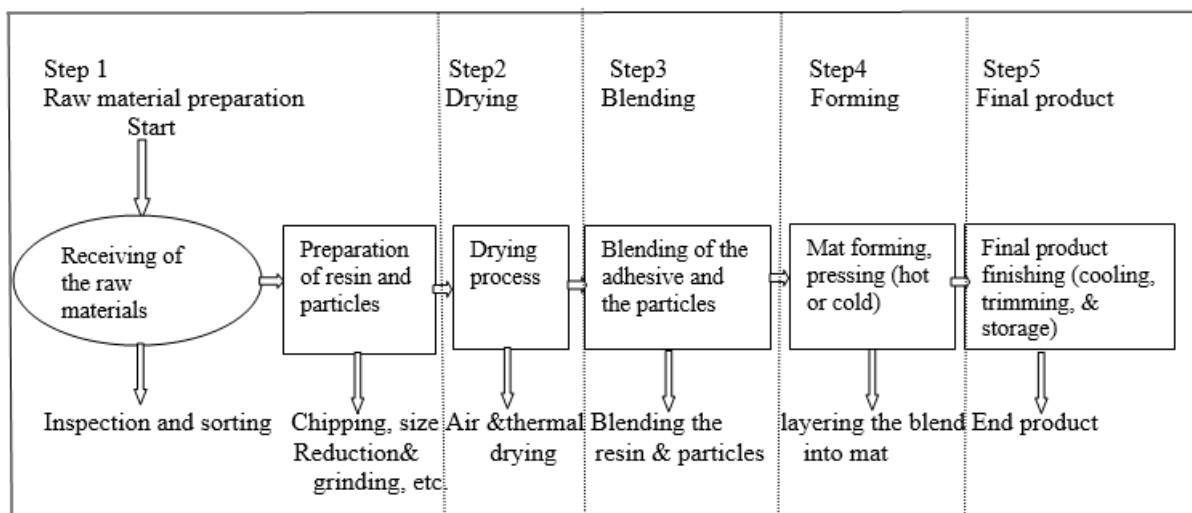


Figure 2-6 Major panel manufacturing process

The advantages of engineered wood panels over virgin wood include the following (Thoemen et al., 2010).

- While wood is anisotropic, its characteristics are uniform throughout its mass. The look of the different species varies greatly. Furthermore, they exhibit superior features such as density, strength, and durability, which are crucial in the creation of products.
- Increased resistance to bacteria, fungus, and insects.
- Capability to create panels with larger proportions than solid wood.
- Customized features include low heat conductivity, fire resistance, increased bio-resistance, and improved surfaces with a variety of ornamentation.

- When compared to wood, it has better properties in terms of splitting, cracking, and shrinkage.
- Panels manufactured from logs are less expensive. For its production, wood byproducts (such as chips, sawmill shavings, or even sawdust) and recycled wood may be used. Small trees and damaged wood can be used in this fashion that would otherwise go to waste.

Particleboard is the most commonly used material in interior and outdoor applications such as flooring, walls, ceilings, office dividers, bulletin boards, cabinets, furniture, counter and desk tops (Wang et al., 2002). Their production from lignocellulosic materials other than wood provides an alternative solution to manufacturers in cases of wood shortage, provides a value-added application to materials that would otherwise be considered waste and useless, and allows countries without forests to participate in an industrial sector that would otherwise be impossible due to their specific landscape.

2.10 Agrowaste Characterization

Many tests are used to characterize the biomass in order to quantify the chemical compositions that play a crucial role in making the board. These tests encompass the physio-chemical characteristics.

2.10.1 Moisture Content

The process of determining moisture content comprises weighing samples into a pre-weighed dish and drying them to a constant weight in a 105°C oven. After that, the percent moisture content (MC) is computed as a percentage weight loss before and after drying. Wet and dry weights are used to calculate the moisture content (Kalanatarifard & Yang, 2012).

2.11 Composite Production Methods

Composites are produced utilizing a range of manufacturing methods, including but not limited to (The Welding Institute, 2024):

- Wet lay-up
- Spray-up
- Injection molding
- Resin transfer molding
- Vacuum infusion
- Filament winding
- Pultrusion
- Prepreg
- Compression molding

Wet Lay-up

It involves layering reinforcement materials and wet resin in a mould, gradually building up the component until the desired thickness is attained. The resin is then cured, possibly with added heat, to create the final product. This technique is frequently utilized in the marine sector for preparing components with glass-fibre-reinforced polyester resins (Harussani et al., 2022). While material expenses are modest and the method offers flexibility, it requires significant manual labour and is associated with elevated emissions of styrene.

Spray-up

This technique is commonly utilized in composite manufacturing, involves applying chopped fibre reinforcement and wet resin onto a mold using a specialized spray gun until the desired material thickness is achieved. After this application process, the resin undergoes curing to form the final component.

Compared to traditional wet lay-up methods, spray-up offers several advantages. It is known for its efficiency and speed, making it suitable for mass production scenarios. Additionally, the process tends to be more cost-effective due to reduced labour requirements and faster production cycles. However, it's important to note that while spray-up yields quicker results,

the resulting composite may exhibit slightly lower mechanical properties compared to those fabricated using wet lay-up techniques.

Spray-up is widely used across industries, particularly in manufacturing large and relatively simple structures like bathtubs, boat hulls, and storage tanks. Its versatility and cost-effectiveness make it a preferred choice for projects prioritizing rapid production and moderate mechanical strength.

Injection Molding

It represents a manufacturing technique where bulk molding compound is first heated and then injected into a heated mold. Under pressure, the compound cures to form the desired component. This approach is highly effective for manufacturing small components with short cycle times. However, due to the significant initial investment required for tooling, injection molding is generally best suited for medium to high volume production runs.

Resin Transfer Moulding (RTM)

In this method, a fibre preforms or fabric is placed into a mold that has been heated to the certain temperature. Within this mold, reactive resin is then blended and introduced into the setup under controlled pressure conditions (Ageyeva et al., 2019). Throughout the process, pressure is sustained until the resin undergoes complete curing, after which the manufactured part is extracted from the mold. Known for its adaptability, this technique excels in manufacturing complex parts capable of withstanding substantial loads, making it a staple across various industrial domains.

A closely related process, known as vacuum-assisted resin transfer molding (VARTM), utilizes vacuum pressure on the sealed mold during the resin injection phase. This method allows for the infusion of resin at low pressure levels, thereby diminishing the stress exerted on the tooling. As a result, VARTM facilitates the utilization of larger and more cost-effective molds, thereby making it feasible to produce expansive structures such as boat hulls or wind turbine

blades at a reduced expense.

Another variant, structural reaction injection moulding (SRIM), utilizes highly reactive resins that can cure without the need for heating the mold, although heating is often employed to expedite the curing process and reduce cycle time.

Vacuum Infusion

Vacuum involves utilizing vacuum pressure to enable a low-viscosity resin to permeate a fibrous preform. In this process, the resin is guided to spread evenly across the surface of the preform before gradually permeating through its entire thickness. This approach is strategically designed to minimize the resin's travel distance within the preform, ensuring optimal saturation and enhancing the overall quality of the composite. The technique's efficiency in resin distribution makes it especially well-suited for the production of sizable components such as boat hulls or wind turbine blades, where uniformity and structural integrity are paramount. By reducing the resin's path through the preform, vacuum infusion not only streamlines the manufacturing process but also results in stronger, more durable end products capable of withstanding demanding operational conditions. One notable advantage is that the tooling does not need to withstand significant loads during the infusion process, enhancing its suitability for manufacturing various structural parts.

Filament Winding

This technique involves passing a fibre tow through a bath of resin and then applying it, while under tension, onto a convex mandrel. While the mandrel rotates, the fibre is carefully deposited in the desired configuration until reaching the desired thickness. Subsequently, the composite material undergoes the curing process, optionally with the application of elevated temperatures if deemed necessary. This process is highly adaptable for automation, making it suitable for high-volume production. It is commonly utilized for manufacturing tubular structures like pipes and driveshafts, as well as more specialized components such as pressure

vessels or monocoque bicycle frames. In applications involving pressure vessels or bicycle frames, the mandrel remains inside the finished component. An alternative method involves the use of pre-impregnated fibre tows or slit prepreg, eliminating the necessity for a resin bath but requiring a curing phase at high temperatures. This variation offers increased efficiency and precision in resin distribution, contributing to the production of high-quality composite components.

Pultrusion

Pultrusion, a commonly employed production method, begins with the retrieval of fibre tows from a creel, followed by their immersion in a resin bath. Afterwards, these impregnated fibres are drawn through a heated extrusion die, initiating the resin-curing process. This results in the formation of an extruded component characterized by reinforced fibres arranged in the axial direction and maintaining a consistent cross-sectional shape throughout.

The versatility of pultrusion is evident in its diverse applications, ranging from the fabrication of gratings, ladder sections, and bridge components to handrails and beyond. What sets pultrusion apart is its remarkable potential for automation, enabling manufacturers to achieve high efficiency and cost-effectiveness in production processes. This automation capability streamlines operations, enhances productivity and ensures consistent quality in the manufactured components. Moreover, it utilizes raw materials that are relatively low in cost, making it particularly suitable for high-volume manufacturing processes.

Prepreg

Prepreg, short for pre-impregnated fibre, comprises fibres, fabrics, or mats that have been saturated with resin. Thermosetting prepregs contain hardeners in the resin, necessitating refrigerated storage due to their limited shelf life. Prior to use, the prepreg must be brought to room temperature to prevent condensation, and plies are then cut into the desired shape and orientation. These plies are layered in a mold to achieve the desired thickness, with a roller

used to prevent air entrapment. The laminate is then enclosed in a vacuum bag, which is evacuated, and the part is cured either in a conventional oven or an autoclave, with added pressure. Autoclave processing results in lower porosity and superior mechanical properties, albeit with a slower cycle time and the need for expensive equipment, particularly for larger components. Prepreg is employed in applications demanding high mechanical properties where the expense of processing can be justified, such as aerospace structures, sporting goods, and wind turbine blades.

Compression Molding

It is a manufacturing technique commonly employed in the production of composite components. The process entails loading a mixture of fibre and resin, usually in the form of sheet molding compound (SMC) or bulk molding compound (BMC), into a preheated mold. Once the mold is sealed, pressure is applied to compact the material and facilitate the curing of the resin. (Greene, 2021). A notable benefit of compression molding lies in its capacity to manufacture components with a Class A surface finish, making it ideal for applications where aesthetics is important. The process is known for its similarities to the stamping process used in sheet metal fabrication, which has led to its widespread adoption in the automotive industry for manufacturing various interior and exterior components.

However, it's important to note that compression molding entails a significant investment in heated tooling, making it more suitable for medium to high volume production runs where the cost can be justified. Although there's an initial investment required, the process provides benefits in terms of effectiveness and consistency, making it a frequently selected option for industries seeking high-quality, high-volume production of composite parts.

Hot Compression Molding

Hot compression molding is a type of molding that involves placing the composite in an open, heated tool first. The tool is closed, and pressure is applied to drive the material into contact

with all tool regions, with the heat and pressure being constant until the material has cured. The key benefits for this process include:

- Single step molding process
- Fast cure times and short modified times (Sub 5-minute modified times for automotive application materials)
- Reduced tooling investment (vs metal forming processes)
- Highly automatable
- Potential to redeploy existing pressing infrastructure

The typical applications areas include the high-rate manufacture of structural and non-structural components for serial automotive and high volume (and typically smaller size) aerospace parts.

2.12 Characterization of Coconut Shells (CS) Composites

The coconut shell could be used for composites; a composite created by (Bledzki et al., 2010) using a coconut shell microparticle as a reinforcement and polypropylene as a binding agent. Concrete can be filled with a coconut shell, according to (Leman et al., 2016). Using a polylactic acid matrix, (Chun et al., 2012) investigated the characteristics of a bio-composite made of coconut shell particles. The bio-composite of coconut shell particles has good mechanical properties, which were dramatically altered by the addition of nanoparticles, according to their findings (Chun et al., 2012; Vasu et al., 2017) investigated a high-density polyethylene composite packed with coconut shell particles. Because of the coconut shell filler, the composite was said to have exceptional mechanical qualities. Several investigations have been carried out on coconut shell powder composites with epoxy resin. (Singh et al., 2013) employed micro-sized coconut shell particles in conjunction with epoxy to create a composite. Their findings revealed that adding microparticles to the composite enhanced its flexural strength and density.

(Somashekhar et al., 2018) used an epoxy matrix to blend coconut shell powder with tamarind shell powder to create a composite. The tamarind shell powder was discovered to increase the composite's mechanical qualities. (Durowaye et al., 2014) also used an epoxy resin matrix to create a composite by combining coconut shell powder (40 meshes) with palm fibre. When compared to similar research, however, the reported composite flexural strength was quite low.

2.13 Characterization Techniques

Analytical techniques encompass a range of sophisticated tools and methodologies that delve deep into the structural, chemical, and thermal attributes of coconut shell composites. Through these techniques, researchers can uncover details about the composition, morphology, interfacial interactions, and thermal stability of these materials, this knowledge forms the foundation for the development of tailored composites with enhanced capabilities and wider relevance across diverse sectors. Below are several frequently utilized methods:

2.13.1 Scanning Electron Microscopy (SEM)

This technique is utilized to analyse the microstructure of coconut shell composites. This technique provides high-resolution images of the surface morphology, allowing researchers to observe the distribution and arrangement of coconut shell particles or fibres within the composite matrix. SEM images can reveal details such as particle size, shape, orientation, and interfacial bonding between the coconut shell and the binding matrix (Akhtar et al., 2018; Zhao et al., 2018).

2.13.2 Fourier-Transform Infrared Spectroscopy (FTIR)

In this work, FTIR served as a tool for the chemical examination of coconut shell composites. Through the analysis of the material's infrared spectrum, FTIR can discern the functional groups existing in both the coconut shell and the binding matrix. This information is crucial for understanding chemical interactions, bonding mechanisms, and compatibility between the components of the composite. FTIR can also detect any chemical modifications or treatments

applied to the coconut shell particles or fibres prior to composite fabrication (Khan et al., 2018)

2.13.3 Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis

(TGA)

Thermal Analysis Techniques are utilized to explore the thermal properties of coconut shell composites. DSC, in particular, measures heat flow linked to transitions like melting, crystallization, and glass transitions. DSC can provide information about the thermal stability, melting behaviour, and crystallinity of the composite material. Another method employed for assessing the thermal degradation behaviour of coconut shell composites is Thermogravimetric Analysis (TGA). This technique monitors changes in mass relative to temperature variations, aiding in the evaluation of the composite's thermal stability and decomposition kinetics.

These analytical techniques allow researchers to gain valuable insights into the microstructure, chemical composition, and thermal behaviour of coconut shell composites, aiding in the optimization of fabrication processes and the development of composites with customized characteristics suited to particular uses (Yulianto et al., 2023)

2.14 Research Gap

Based on the literature reviewed, the distinctiveness of the current research can be seen from:

Using extracted coconut shells particles with potato tuber waste and water as a plasticizer to make green particleboard for housing construction applications purposes.

Determination of mechanical and physical properties of water ethanol extracted coconut shell particles reinforced potato tuber waste board.

3 MATERIALS AND METHODOLOGY

3.1 Introduction

In this chapter, the process of fabrication the coconut shell particle boards, the experimental design used, characterization and analysis of chemical (lignocellulosic contents) and physical properties of coconut shell for both raw and residue, evaluation of physical and mechanical properties of the particleboards are described. Figure 3–1 shows the methodological process followed in achieving the objectives of this study

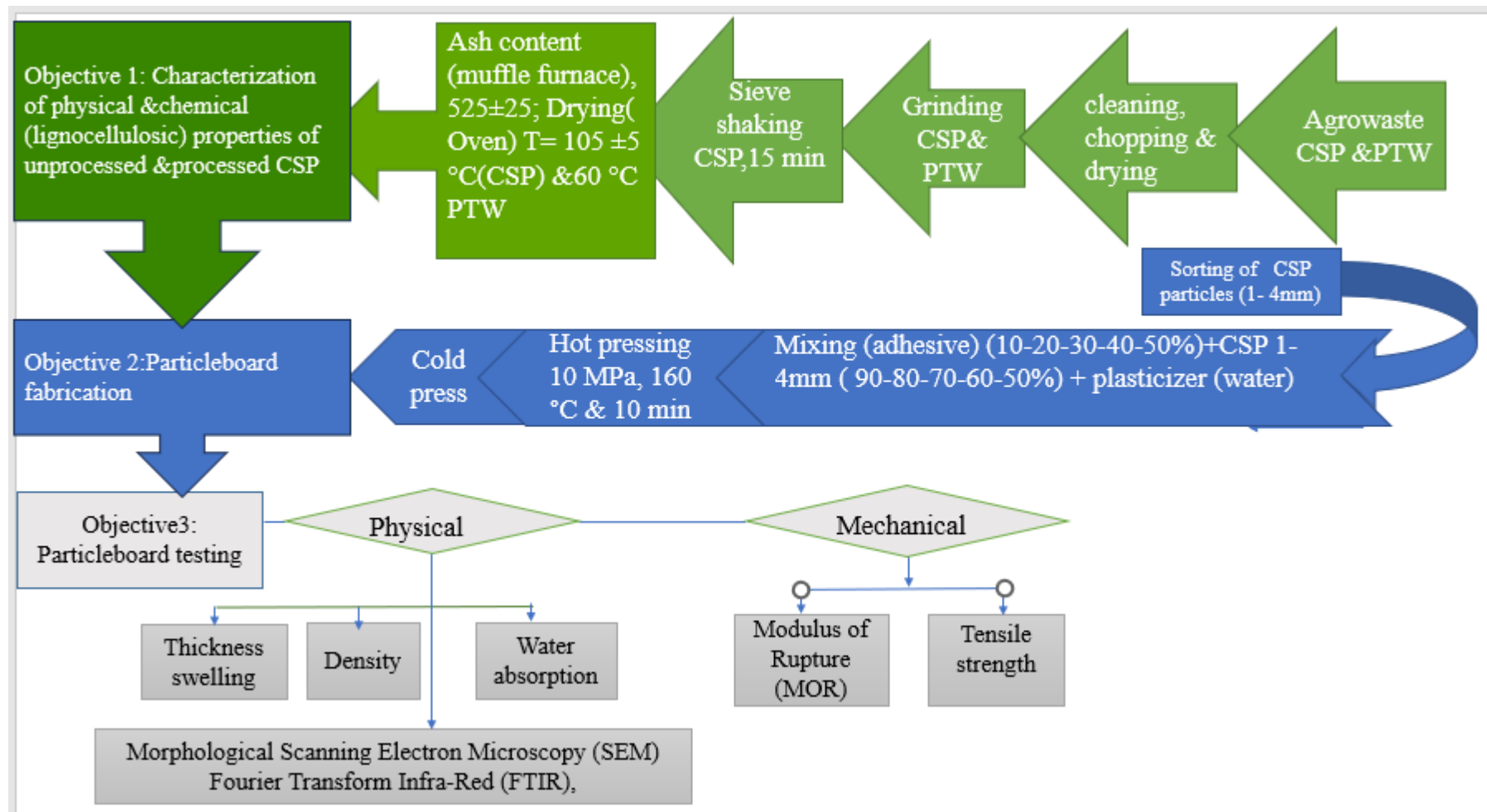


Figure 3-1 Methodological process in relation to the research objectives

3.2 Materials and Reagents

The main materials used in this research are given in Table 3.1.

Table 3-1 Materials used in coconut shell particleboard fabrication

Material and its Specifications
Coconut shells
Potato tuber waste
Sulfuric acid % 98(H_2SO_4)
Sodium chlorite 80% (NaClO_2)
Sodium hydroxide Pellets 97% (NaOH)
Acetone 99% ($\text{C}_2\text{H}_5\text{CO}$)
Ethanol Absolute ($\text{C}_2\text{H}_5\text{OH}$) 99.7%
Acetic acid Glacial 99.7% (CH_3COOH)
Distilled water
Digital micrometre
Mold Release Agent (Thin Aluminium foil)

3.2.1 Material Collection and Preparation

3.2.1.1 Shells Particles

Coconut shells were purchased from Amor Coco Kenya LTD, Mombasa, Kenya while potato tuber waste was obtained from Eldoret local market, Uasin Gishu County, Kenya. Coconut shells were washed and air dried for seven days, oven dried for 5 hours, ground for 20 seconds using commercial grinder at 25000 rpm and capacity of 2000 gram (Figure 3–2) at manufacturing, industrial and textile engineering (MIT) Lab.



Figure 3-2 Commercial grinder

3.2.1.2 Particle Size Distribution

The ground coconut shell particles were agitated by taking 1000 grams of them using Liya sieve shaker at (MIT Laboratory) as shown in figure 3–3 for 15 minutes at different trays from 4 to < 1 mm and the graph of particle size distribution was plotted.



Figure 3-3 Vibratory sieve shaker machine (Liya sieve shaker)

3.2.1.3 Coconut Shell Pretreatment

Coconut shell of different particle sizes was pretreated (to extract the colorants) using ethanol and deionized water at liquor ratio of 1:10 using reflux method for 1 h using water bath (model

WB10) shown in Figure 3-4 at chemistry lab; then oven dried at 105°C for 3 h. the pretreated particles were used for particleboard development.



Figure 3-4 Water bath

3.2.1.4 Potato Tuber Waste Preparation

Potatoes were purchased from Eldoret local market, Uasin Gishu County, Kenya. They were washed using tap water to remove impurities and debris, chopped manually into small pieces (approx. 1-2 mm sizes), air dried for 4 weeks before grinding using commercial grinder (Figure 3-2).

3.2.1.5 Reinforcement and Resin Preparation

Coconut shells (CS) were purchased from Amor Coco Kenya LTD. These were peeled and scraped, washed and air dried for 7 days, oven dried at 105 °C for 5h, ground at 25000 rpm for 20s, after that the powder was agitated for 15 min to be separated at different sizes of 1+<1, 2, 3.15 & 4 mm respectively Figure 3-5. All different sizes of the CS particles were then water ethanol pretreated by reflux method, for 1h at LR =1:10. Potato tuber (*Solanum tuberosum*) waste was cleaned, chopped, air dried for 7 days, oven dried at 50 °C for 5h and ground and then agitated and sorted to different sizes from size 4 to 1+<1 mm.



Figure 3-5 Reinforcement preparation (washed, dried, ground and sorted to different sizes)

3.2.1.6 Production of Thermoplastic Starch (TPS)

The dried potato tuber waste powder Figure 3-6 was mixed with water thoroughly using commercial blender at 25000 rpm for 1 minute in a ratio of 70:30 by weight at room temperature and 65 RH (relative humidity). The mixture was then put in the mould for hot compression.



Figure 3-6 Potato tuber waste powder

3.2.2 Characterization of the Raw Materials

Raw and pretreated coconut shell particles were characterized in terms of lignocellulosic compositions and physical properties as follows:

3.3 Methods

3.3.1 Characterization of Coconut Shells

3.3.1.1 Moisture Content

An oven (model LDO–150F) Figure 3-7 located at MIT lab was used to determine the moisture content in accordance with (Arun et al., 2014) the following procedure was followed:

1. Specimens were stored in an individual vapor-tight containers.
2. Crucibles were oven dried for 2hrs
3. 10 g from raw and processed coconut shell (CS) were weighed on a balance and placed in an oven until reaches equilibrium ($T= 105\pm2$ °C).
4. Samples were weighed after oven dried during the interval of the day (each 1hr).
5. CS samples were dried to constant weight.
6. Moisture content on wet basis (M_{web}) given by Equation 3-1

$$M_{web} = \frac{(m_i - m_f)}{m_i} \quad \text{Equation 3-1}$$

- a. Where, m_i and m_f are initial and final weight of samples respectively. (Arun et al., 2014)



Figure 3-7 Oven

3.3.1.2 Determination of Klason Lignin Content of Coconut Shell Particles

This was carried out according to TAPPI T 222 om-02 standard (Dence, 1992). Ten samples of coconut shells were used.

1. 1 g of oven-dried extract-free specimen was weighed and put into a 30 ml beaker.
2. 15 ml cold (10 – 15 °C) 72% sulfuric acid (H₂SO₄) was slowly added with constant stirring to ensure that the specimen and acid was thoroughly mixed.
3. During this operation, the mixture was frequently stirred and maintained in a water bath at 20 ± 1 °C for 2 h.
4. The solution was transferred into Erlenmeyer flask, and then the sulfuric acid strength was brought down to 3% by adding 575 ml of hot distilled water.
5. Then the solution was boiled for 4 h using reflux condenser.
6. Subsequently, the insoluble lignin was allowed to settle and filtered overnight
7. Then it was washed with hot distilled water and dried to constant weight in an oven at 105°C.
8. The Klason lignin content was calculated using Equation 3-2:

$$\text{Klason lignin \%} = \frac{100 \cdot A}{W} \quad \text{Equation 3-2}$$

Where: **A** = Weight of Klason lignin, g **W** = Oven-dried weight of test specimen, g

3.3.1.3 Determination of Acid-Soluble Lignin

The following procedure according to TAPPI Useful Method UM-250 (TAPPI 1985b) (Dence, 1992) was followed:

1. A sample of the clear filtrate (or decantated) from the second stage acid hydrolysate in the acid-insoluble lignin determination was placed in an absorption cell having a 10-mm light path.
2. The absorbance was measured at 205 nm using 3% H₂SO₄ as a blank or reference solution. When the absorbance was higher than 0.7, the filtrate was then diluted in a

volumetric flask with 3% H₂SO₄ to obtain an absorbance reading in the range 0.2 to 0.7

3. The diluted filtrate was used as a test specimen for absorbance measurement.
4. The lignin content in the filtrate was calculated according to the following expression of Beer's Law Equation (3-3):

$$\text{Lignin (g/l)} = \frac{\text{Absorbance (A)}}{b \text{ (light path in cm)} * a \text{ (absorptivity in } 1 \text{ g}^{-1} \text{ cm}^{-1})} \quad \text{Equation 3-3}$$

- $b=1$; $a=110 \text{ l g}^{-1} \text{ cm}^{-1}$
 - Hence
 - Lignin (g/l), $B = \frac{A}{110}$, in undiluted filtrate
 - Lignin (g/l), $B = \frac{A}{110} D$, in diluted filtrate
 - where $D = \frac{V_D}{V_O}$; V_D = Volume of diluted filtrate
 - V_O = volume of original filtrate taken
5. The acid-soluble lignin content in sample is calculated from Equation 3-4

$$\text{Lignin, \%} = \frac{B * V * 100}{1000 * W} \quad \text{Equation 3-4}$$

- Where V = total volume of the filtrate, that is, 575 ml for wood, W = oven-dry weight of wood or pulp sample, g.

3.3.1.4 Determination of Holocellulose

This was carried out according to modified Wise et al. (1946) and (Jani et al., 2014), Four samples of coconut shell particles were used following this procedure

1. This operation was carried out in a well-ventilated cupboard due to toxicity of chlorine dioxin (Wise et al. 1946).
2. 2 g of oven-dried extract-free sample was weighed in a 250 ml beaker.
3. 100 ml of distilled water was added, followed by 1.5 g sodium chlorite (NaClO₂) and 5 ml of 10% acetic acid.

4. The beaker was placed into a water bath at 70 °C and heated for 30 minutes with frequent stirring.
5. Then 5 ml of 10% acetic acid and an additional of 1.5 g NaClO₂ after 30 min. The alternate additions of acetic acid and NaClO₂ continued at 30 minutes intervals until 6 g of NaClO₂ was added, after that, the beaker heated for 30 min after the last addition of NaClO₂.
6. The specimen was allowed to cool until it was below 10 °C and filtered in a weighed filtering crucible by washing with iced-distilled water.
7. Subsequently, it was washed with acetone and allowed to be air-dried. Finally, the residue transferred into a desiccator and weighed at daily intervals until the specimen reached a constant weight.
8. Holocellulose was calculated using Equation 3-5

$$\text{Holocellulose weight \%} = \frac{100 \cdot B}{A} \quad \text{Equation 3-5}$$

Where: **A** = Oven-dried extract-free specimen weight, g., **B** = the constant weight of specimen after air dried and desiccated, g.

3.3.1.5 Determination of α-Cellulose Content

Alpha-cellulose was determined according to TAPPI T 203 cm-99 (TAPPI 1999b) (Jani et al., 2014). Ten samples of coconut shell particles were used.

1. 2g of holocellulose was put in a beaker containing 3ml of 17.5 NaOH.
2. After 5 min, additional of 17.5% NaOH (3 ml) was added.
3. The content was allowed to stand for 35 minutes, a total of 42 min contact time.
4. After washing with 60 ml of distilled water, 5 ml of 10% acetic acid was added and 5 min later, the alpha-cellulose was washed with distilled water (60 ml), and then finally with acetone (20 ml). After washing, the sample was oven dried to a constant weight,

and the alpha cellulose content was calculated based on oven dried weight.

5. The hemi-cellulose content was calculated by the weight difference between the two, by subtracting the weight of alpha cellulose from that of holocellulose

3.3.1.6 Determination of Ash Content %

Ash content method (T 211 om-02) (TAPPI, 1993), the furnace (type ELF 11/14B 220–240V 1PH+N) Figure 3–8 and oven Figure3–7were used, using the following procedure:

1. Crucible was put into furnace for 1 h to dry.
2. CSP was oven dried into oven for 4h.
3. Then 2 g of CSP was weighed in the crucible and covered with the lid.
4. After that the crucible with the sample was covered with the lid and put into the oven at 525 ± 25 °C for 2 h to avoid the sample from flaming.
5. After that the lid was removed and combusted for 3h.
6. Then the crucible was removed from the furnace, the cover replaced and allowed to cool and placed in a desiccator then cooled to room temperature. The crucible was weighed with ash.
7. Ignition and weighing repeated until the weight of the ash is constant.
8. The ash content was calculated from Equation 3-6:

$$Ash, \% = \frac{A * 100}{B} \quad \text{Equation 3-6}$$

Where A = weight of ash, g, B = weight of test specimen, g moisture-free



Figure 3-8 Furnace

3.3.2 Particleboard Fabrication

3.3.2.1 Preparation of the Mold for Making Sample Particleboard

A mold measuring 310×310×20 mm was fabricated using mild steel; a material that could withstand the pressing load (Figure 3–9). A frame measuring 300×300×5 mm was also fabricated to provide smooth finish at the top of the mold (Figure 3–10).

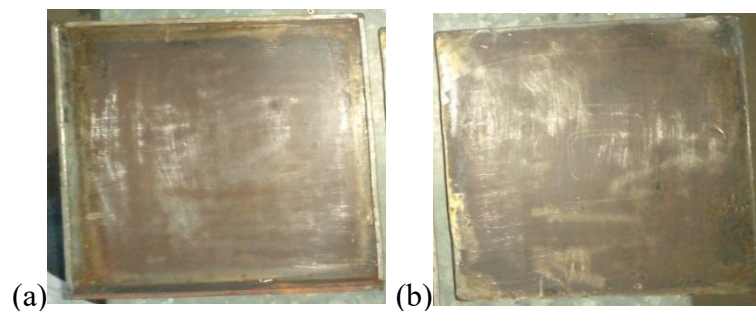


Figure 3-9 (a) Mold for forming particleboard sample (b) mold lid



Figure 3-10 A steel frame

3.3.2.2 Experimental Design

Experiments containing two dependent variables namely particles weight fraction and particles size were conducted using design expert v13 using response surface methodology (RSM) at optimal custom design for both exchanges of the shell sizes and shell weight fraction where the levels were representing the four options of shell sizes and the five weight fractions of the shells as shown in Tables 3-2 & 3-3. The experiment was developed based on variables and levels established from preliminary experiments to ensure optimal design. The variables studied include Coconut shells wt.% and Coconut shells particle size (CSPS), with their respective levels defined as shown in Table 3-2.

All particleboards were produced under consistent conditions to maintain experimental reliability. Specifically, a constant pressure of 10 MPa was applied using a four-column hydraulic press (model Yz32–80T) (refer to Figure 3–11). The pressing was conducted at a temperature of 160 °C for a curing time of 10 minutes, followed by a cold press for 3 minutes to finalize the production process.

The weight fraction used in terms of weight of coconut shell particles to potato tuber waste was 10:90, 20:80, 30:70, 40:60, 50:50, while the particle sizes of the coconut shells were 1, 2, 3.15, and 4 mm, these ratios and particles sizes were considered in order to examine the effects they had on the properties of particleboards. The experimental design, generated using design software, resulted in a total of 16 runs to explore the effect of the selected variables. Accordingly, 16 different particleboards were fabricated using treated coconut shell particles. Each run was prepared in three replicates to ensure reliability of the results. Furthermore, the fabrication process was repeated for the particleboard with the optimal treatment combination to confirm its performance.



Figure 3-11 Four-column hydraulic press

Table 3-2 The experiment development coded table

Variable		Units	Type	Levels	L1	L2	L3	L4	L5
Coconut wt. %	shells	%	Discrete	5	-1	-0.5	0	0	1
Coconut particle (CSPS)	shells size	mm	Discrete	4	-1	-0.333333	0.333333	1	

Where;

- **L1 = -1:** This represents the lowest experimental value, say, 0% coconut shells by weight; the smallest particle size, e.g., 1 mm (or a specific small size).
- **L2 = -0.5:** This represents a mid-low value, such as 25% coconut shells by weight; **-0.3333:** This could represent a small-to-medium particle size, e.g., 0.5 mm.
- **L3 = 0:** This represents a neutral value, such as 50% coconut shells by weight; **0.3333:** This could represent a slightly larger particle size, say 0.75 mm (or another intermediate value).
- **L4 = 0.5:** represent a mid-high value, such as 75% coconut shells by weight; **1:** represent the largest particle size, e.g., 1.5 mm or higher.
- **L5 = 1:** This represents the highest experimental value, 100% coconut shells by weight.

Table 3-3 The experiment development uncoded table

Run	Factor1: coconut shell wt. %	Factor2: coconut particles size
1	30	2
2	50	1
3	50	1
4	30	1
5	10	4
6	20	2
7	20	1
8	50	3.15
9	10	2
10	40	3.15
11	30	2
12	10	2
13	20	1
14	20	4
15	30	2
16	40	4

3.3.2.3 Particleboard Fabrication

A particleboard sample measuring 300 mm x 300 mm x 5 mm was fabricated using the hot compression method. Boards with different particle size and weight fraction of the particles were produced in order to investigate their effects on the properties of the board. The following procedure was followed in fabrication process;

1. The mold was cleaned and heated up to 160 °C.
2. The particles were mixed with resin manually and stirred until a homogenous mixture was obtained
3. A protective treatment of the mold surface with the mold release agent was applied.
This mold release agent prevented the particleboard from sticking onto the mold.
4. After this, a homogenous mixture of the resin and particles was put into the mold.
5. Then a compression pressure of 10 MPa was applied on the mixture (Figure 3-11) consolidating the mixture into a composite.
6. After hot compressing of the board for 10 minutes, it was subjected for an additional cold compression for 3 minutes and removed from the mold.

7. The same procedure was repeated as required.
8. The boards were left to dry for 4 weeks at room temperature and 65 relative humidity (RH).



Figure 3-12 Coconut shell particles and potato tuber waste powder paste mixture

3.3.3 Characterization of the Particleboard

The particleboards were characterized in order to determine their physical and mechanical properties as follows:

3.3.3.1 Physical Properties

Water absorption and thickness swelling of the particleboard samples were determined according to the ASTM standard method (ASTM D1037-99). The samples were cut using a hacksaw in 50X50X5 mm and soaked in water at room temperature (20-22°C) for 2 h and 24 h to determine short- and long-term properties, respectively. The weight and thickness of the sample were measured before and immediately after soaking and used to calculate water absorption and thickness swell, which were reported as percentages of the values before soaking.

Water absorption and thickness swelling tests were conducted as per EN 317 (1993) standard using electronic weighing machine and a water bath. The steps were as follows;

1. Samples measuring 50 x 50 mm were cut randomly from the fabricated board.
2. Measurements were done to accuracy of 0.01mm at the intersection of the diagonals.

3. Conditioning: conditioned to constant at R.H $65 \pm 5\%$, temp. 20 ± 2 °C.
4. Measurement of thickness and weight were done before immersion in water.
5. Specimens were immersed in the water bath with face vertical in clean still water, having pH
Of 7 ± 1 and temperature maintained at 20 ± 1 °C.
- 6 Specimens were separated from each other and from the sides of water bath and bottom and
Top covered by 25 ± 5 mm through the testing period.
7. After immersion (2 and 24 h), excess water was removed, cleaned and thickness was measured
To record the increase in weight and thickness of the samples
8. The water absorption and thickness swelling were calculated utilizing equation 3-7 and 3-8, respectively

$$A_w = \left(\frac{W_f - W_i}{W_i} \right) * 100 \quad \text{Equation 3-7}$$

Where A_w = *water absorption* (%), W_f = final weight, W_i = initial weight

$$G_t = \left(\frac{t_2 - t_1}{t_1} \right) * 100 \quad \text{Equation 3-8}$$

Where G_t = *thickness swelling* (%), t_2 = final thickness, t_1 = initial thickness

The density of the board was conducted using a weighing machine according to EN 323:1994 standard for measuring density.

1. Specimens measuring 50 mm x 50 mm were cut randomly from the fabricated boards
2. The samples were measured (length, width, and thickness) and weighed
3. The actual density was then calculated using the following equation:

$$\text{Density (g/cm}^3\text{)} = \frac{W_a}{V_a} \quad \text{Equation 3-9}$$

Where: W_a =air dry weight V_a =air dry volume

3.3.3.2 Mechanical Properties

Finished particleboards were cut using hacksaw into various specimens according to standard method (ASTM D1037) and EN 310: 1993. The rectangular 51 ×175 and 50×150 mm pieces were used for Tensile Strength (TSP) determination and three-point-flex measurement of (MOR), respectively the tests were done in three replicates of 16 runs. The mechanical properties were determined using an Instron testing machine (Model No. TCTN-9110-5KN, Capacity 5000N) with the speed of movable crosshead being 4 mm/min for TS test and 5 mm/min for three-point-flex. Each reported value is the average of three measurements., water absorption, thickness swelling and density properties of coconut shell reinforced whole potato waste composite were determined.

The samples for tensile strength parallel (TSP) to surface testing were cut to the required dimensions using a hack saw, a file and sand paper. The sample preparation in terms of dimensions, gauge, length and speed were performed according to the tensile strength parallel to surface (TSP) (ASTM 1037). The tests were performed using a Universal Testing machine equipped with a 5KN load cell and a cross-head speed of 2 mm/min. For each experimental run, specimen pieces were tested with minimal variances and were tabulated. The tensile strengths of the specimen composites were calculated by dividing the maximum load in Newtons by the original cross-sectional area of the specimen in square meters (Eqn.3- 11).

$$\textbf{Tensile Strength (MPa)} = \frac{\text{Maximum Tensile Load}}{\text{Original Cross-Sectional Area}} \rightarrow \frac{P_{Max}}{A} \quad \text{Equation 3-10}$$

MOR test was conducted according to EN 310: 1993 using universal testing machine (Model No. TCTN-9110-5KN, Capacity 5000N). MOR is determined by applying a load to the centre of the test piece supported at two points; Schematic diagram of a three-point bending test is shown in Figure 3-13. The bending strength (or MOR) of the test piece is calculated by

determining the ratio of the bending moment M at the max load $F_{\max}$, to the moment of its full cross-section.

- a. Test piece size: width 50 ± 1 mm, thickness 5 mm, length = $((20 \times 5) + 50)$ mm = 150 mm
- b. Conditioning: conditioned to constant mass in an atmosphere with a relative humidity $65 \pm 5\%$, and temperature maintained at 20 ± 2 °C.
- c. The following procedure as stated by the standard was followed:
 1. The thickness was measured at the intersection of the diagonals and the width at the mid-length
 2. The distance between the centres of the supports was adjusted to within 100 mm
 3. The distance between the centre of support was measured to within 0.5 mm
 4. The test piece was placed flat on the supports, with its longitudinal axis at right angles to those of the supports with the centre point under the load.
 5. Load was applied at constant crosshead movement throughout the test at which max load is reached within (60 ± 30) s.
 6. Deflection was measured (using dial gauge) in the midpoint of the test piece (below the loading point) to an accuracy of 0.1 mm and this value was plotted against the corresponding load measured to accuracy of 1/5 of the measured value.
 - a. The maximum load was recorded to an accuracy of 1 % of the measured value.
 - b. Test was conducted on two groups of test pieces according to the two directions of the board, i.e., in the longitudinal and transverse directions in each group test half of the test pieces with the 'top face' upward and half with the 'bottom face' upwards.
- c. Calculation

Bending strength (MOR) f_m (in N/mm^2) of each test piece is given by equation 3-11;

$$f_m = \frac{3F_{max} l_1}{2bt^2} \quad \text{Equation 3-11}$$

Where f_{max} is the maximum load in N, l_1 , b and t are the distance between the centres of the support, b is the width of the test piece in mm, and t is the thickness of the test piece in mm.

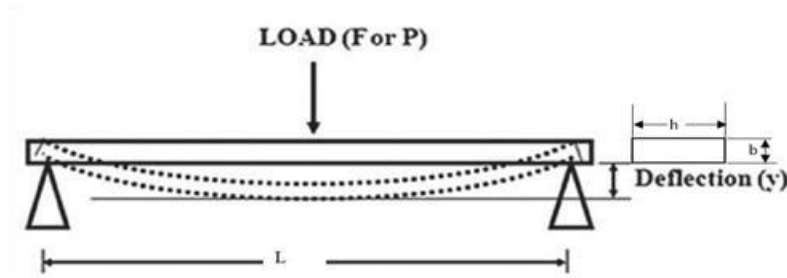


Figure 3-13 Schematic diagram for bending test on universal testing machine

3.3.3.2.1 Fractography Study (Morphological test)

Surface morphology for coconut shell particleboard was investigated using scanning electron microscope (SEM, JOEL, JSM6610LV) in Belgium. The imaging was done on the fractured surface at different magnification.

Scanning Electron Microscopy (SEM) was utilized to investigate the surface morphology and microstructure of the coconut shell particles (CSP), potato tuber waste (PTW) and the fabricated particleboard used in this study. SEM analysis was performed using a (SEM, JOEL, JSM6610LV) in Belgium. Prior to analysis, samples were prepared by mounting CSP and PTW specimens on to aluminium stubs and sputter-coating them with a thin layer of gold/palladium to enhance conductivity and minimize charging effects. SEM images were acquired at magnifications (1600x) to capture microstructural features and surface topography. SEM analysis provided valuable insights into the morphology and structural properties of CSP, PTW and a better understanding of the bonding particle, which informed subsequent processing and evaluation of particleboard samples.

3.3.3.2.2 Thermal Analysis

The tests were done in order to determine degradation temperature of starch, particles, and panel. It was also used to determine changes in substrate weight in relation to changes in temperature.

Specimens weighing 20 mg were heated from 30 to 600 °C at a heating rate of 10 °C/min under a flow of 60 mL of air gas in unsealed aluminium pans corresponds to the first heating stage. The test was performed with a DSC (model: DZ 3320A) (XIANG Yi) (China) differential scanning calorimeter equipment as shown in figure 3–14, A spectrum of the decaying curve was generated from an average of three runs. The endothermic melting of potato tuber waste and coconut shell particles mixture was observed at 160 °C.



Figure 3-14 DSC analyser

3.3.3.2.3 Decomposition

The decomposition of samples was investigated with natural soil burial test (Maran, Sivakumar, Thirugnanasambandham, & Sridhar, 2014). The pH of the soil was 6.7. The soil was kept moist by sprinkling water at a regular time interval to maintain 20–40% humidity. The temperature conditions of compost soil at $T=30 \pm 2$ °C. The samples were cut into 10mm×20mm pieces. Every 7 days, five specimens were removed from the soil, then washed in distilled water and dried in an oven at 60 ± 2 °C for 24 h. Finally, the specimens were

weighted and compared with specimens before testing. The percentage weight loss is calculated using the following equation:

$$WL (\%) = \frac{W_0 - W_1}{W_0} * 100 \quad \text{Equation 3-12}$$

Where W_0 is the initial mass, W_1 is the mass after degradation. The weight loss (WL, %) is the average of at least five specimens of each sample.

4 RESULTS AND DISCUSSION

4.1 Results Overview

This study investigated the use of treated coconut shell particles of different sizes and weight fraction bound with potato tuber waste in the formulation of particleboards. This chapter gives a detailed discussion of the results obtained in this study. The lignocellulosic contents of raw materials and both; mechanical and physical properties of the fabricated particleboards have also been presented.

4.2 Particle Size Distribution

Figure 4–1 shows the particle size distribution of coconut shell particles used in the current study. It is evident that most particle sizes were in the range from 1 to 4 mm and therefore used in current study for particleboard fabrication. The data used in particle size distribution is given in Table 7-1 (in appendix) for reference.

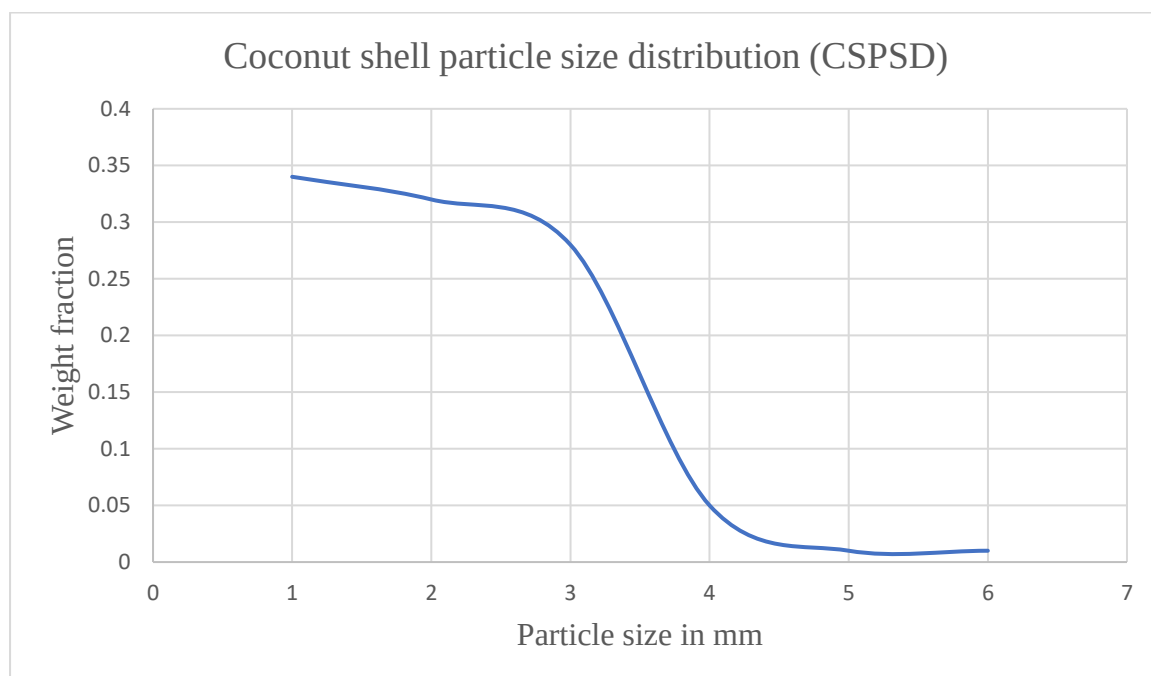


Figure 4-1 Particle size distribution of CSP

4.3 Chemical and Physical Properties of Coconut Shell Particles

The lignocellulosic composition, as well as the moisture and ash contents of raw and pretreated coconut shell particles (CSP), are presented in Tables 7-2 to 7-14 (located in the appendix). A summary of the properties of raw and pretreated CSP is provided in Table 4-1. The moisture content of pretreated CSP was found to be 12.09%, a level that could significantly influence the board properties. To address this, the CSP was dried to a constant moisture content of 6%. The physio-chemical characteristics of CSP were found to be largely consistent with data reported in the literature, as shown in Table 2-1 in the literature review.

Table 4-1 Coconut shell particles lignocellulosic properties

Property	Raw CSP	Pretreated CSP
Acid Insoluble Lignin (AIL)	28.3 ± 4.67	31.5± 2.64
Acid soluble Lignin (ASL)	2.52 ±0.14	2.91 ±0.6
Hot water extractives	6.52 ± 1.26	-
Holocellulose content	56.15 ± 3.47	65.20 ± 2.03
Cellulose %	23.61 ± 0.71	34.65± 2.90
Hemicellulose %	32.53 ± 0.71	30.55 ± 2.90
MC %	5.90 ± 0.61	12.09 ± 1.16
Ash	0.86±0.19 %	0.76±0.18

Cellulose % in CSP residue = 34.65± 2.90

Hemicellulose % in CSP residue = 30.55 ± 2.90

4.4 Mechanical Properties of CSP Particleboard

4.4.1 Tensile Strength and Modulus of Rupture

The tables 7–16 and 7–17 found (in the appendix) for reference, displays the results of tensile strength and modulus of rupture of particleboards made from pretreated CSP using resin content from 50% to 90%. This assessment was done to investigate the effects of matrix mass fraction and particle size on mechanical properties of fabricated boards as shown in Figures from 4-2 to 4-5.

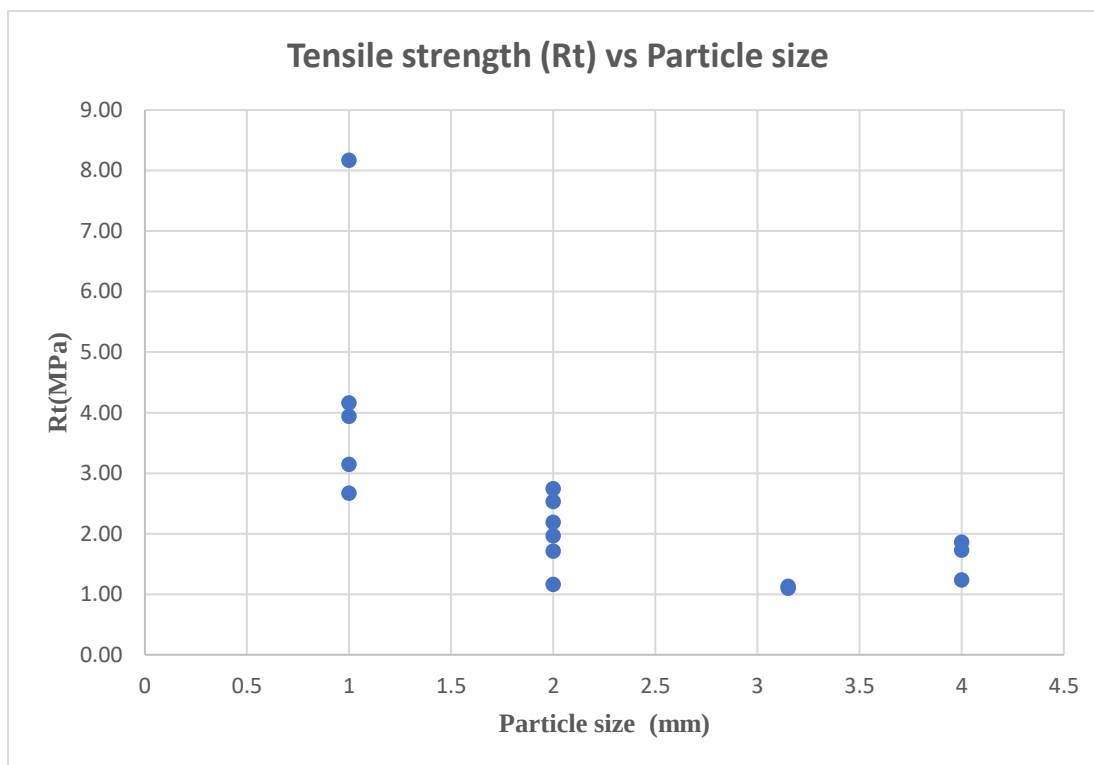


Figure 4-2 Tensile strength vs particle size

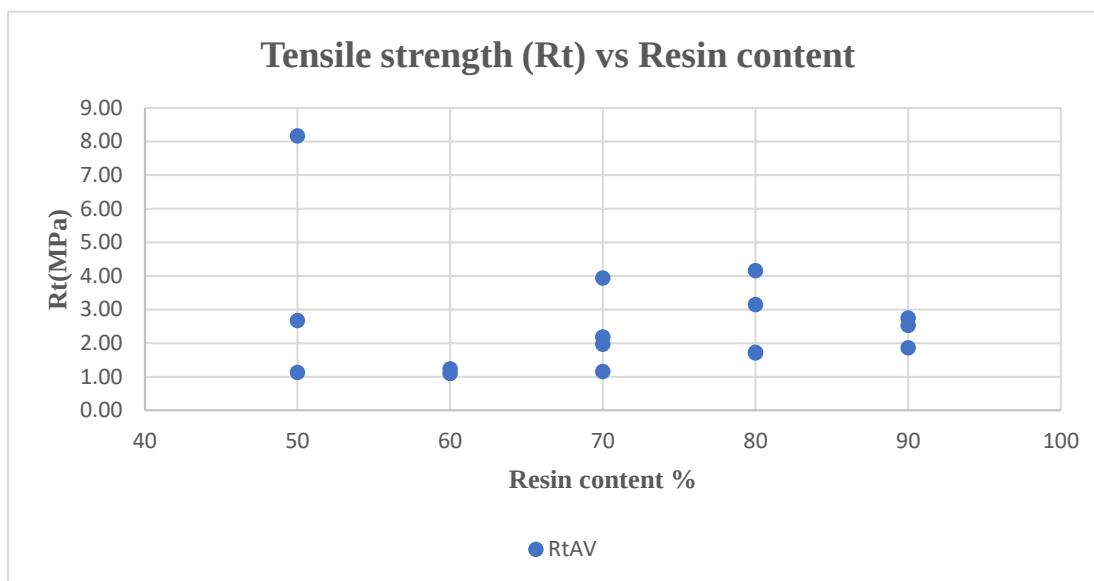


Figure 4-3 Tensile strength vs resin content

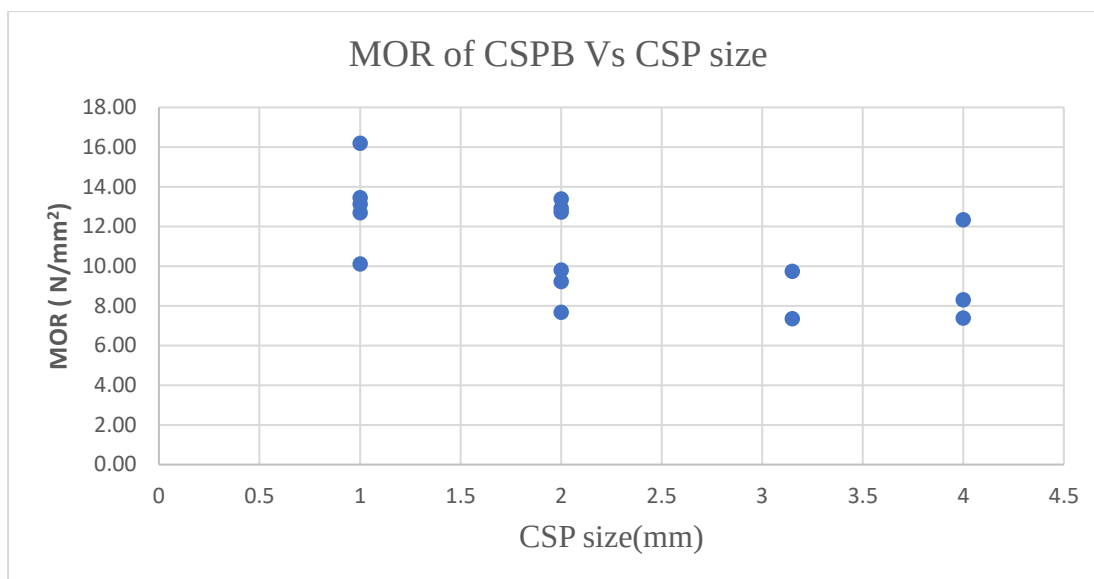


Figure 4-4 Modulus of rupture vs CSP size

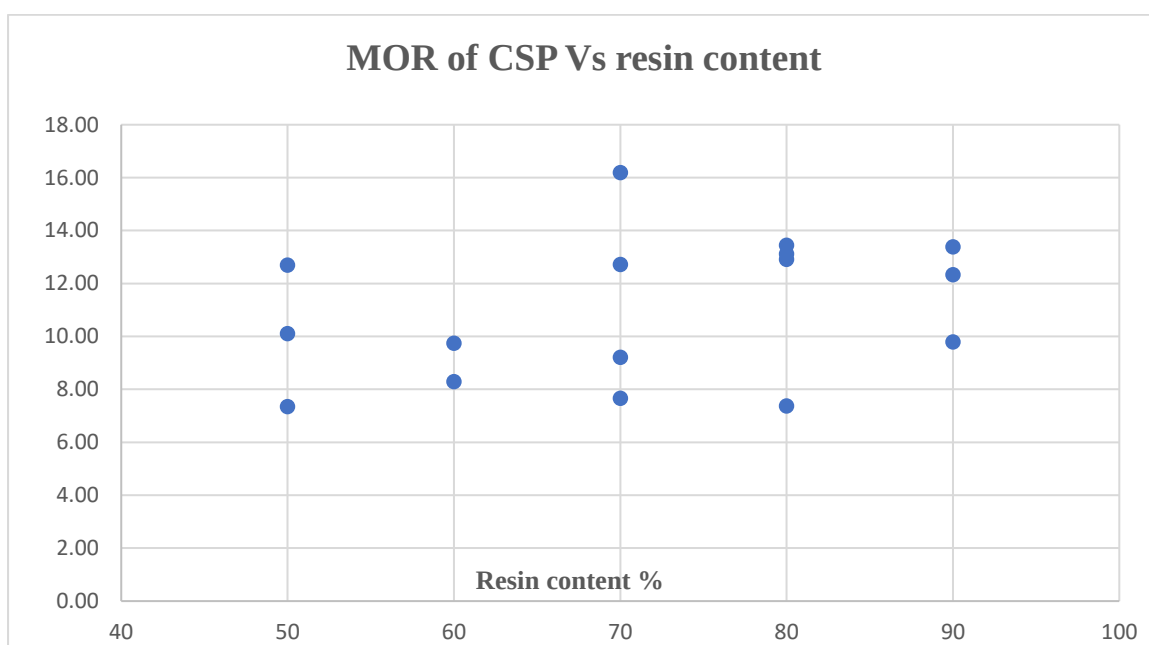


Figure 4-5 Modulus of rupture vs resin content

From figures 4-2 and 4-3 it was observed that the maximum tensile strength was found at the particle size of 1 mm and 50 % of resin content; from Figures 4-4 and 4-5 it was shown that the maximum modulus of rupture of the particleboard was also found at 1mm of particle size and 70% of resin content.

4.4.1.1 Resin Content and Tensile Strength Parallel to Surface (TSP) of Particleboard

Figures 4-2, 4-3, and Table 7-16 found (in appendix) for reference show the graph and value

of maximum tensile strength of the particleboard sample (8.17MPa) against its corresponding resin content (50%) and shell particle size (1mm). It was observed that the tensile strength decreases when the resin content increased. In other words, the highest tensile strength corresponded to 40% particle weight fraction. Several studies have shown that tensile strength of a composite is dependent on the weight fraction of the reinforcement and its strength. However, there is a level over which increase in fibre fraction decreases the strength due to poor bonding (Madueke et al., 2014; Mouritz & Woodhead Publishing Ltd.: Cambridge, 2012; Njoku et al., 2011; Tezara et al., 2016).

The analysis of variance (ANOVA) for the Tensile Strength Parallel to Surface (TSP) of a particleboard manufactured from coconut shell particles with varying resin weight fraction of 50%-90% is shown in Table 4-2. From this analysis, the value of computed P-value was 0.0370 and this was lower than α -value (0.05) indicating a significant difference in the tensile strength parallel to surface (TSP) of the particleboards. This means that resin increment and the reinforcement particle size had effects on the tensile strength Figure 4-6

Factor Coding: Actual

Tensile Strength (MPa)

Design Points:

● Above Surface

○ Below Surface

1.1  8.17

X1 = A

X2 = B

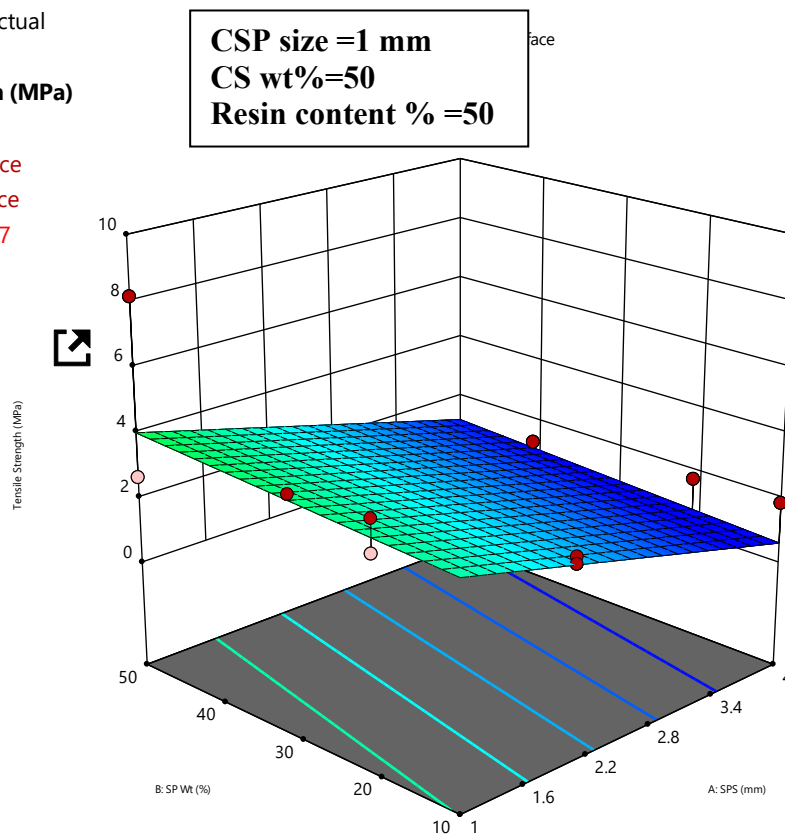


Figure 4-6 Tensile strength Vs resin content and particle size

4.4.1.1.1 ANOVA for Linear Model

Table 4-2 Response 1: Tensile Strength Parallel to Surface

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	18.53	2	9.26	4.29	0.0370	Significant
A-SPS	17.14	1	17.14	7.94	0.0145	
B-SP Wt.	0.6432	1	0.6432	0.2981	0.5944	
Residual	28.06	13	2.16			
Lack of Fit	11.81	8	1.48	0.4542	0.8464	not significant
Pure Error	16.25	5	3.25			
Cor Total	46.58	15				

Factor coding is **Coded**.

The **Model F-value** of 4.29 indicates that the model is significant, with only a 3.70% probability that an F-value this large could occur due to random noise.

P-values less than 0.0500 indicate model terms are significant. In this case A is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

The **Lack of Fit F-value** of 0.45 suggests that the Lack of Fit is not significant compared to the pure error, with an 84.64% probability that such a large Lack of Fit F-value could occur due to noise. Non-significant lack of fit is good; we want the model to fit.

4.4.1.2 Resin Content and Modulus of Rupture (MOR) of Particleboard

The outcome of modulus of rupture (flexural strength) with resin content is displayed in Figures 4-4 and 4-5, and Table 7-17 found (in appendix) for reference. The maximum bending strength (16.20 MPa) of the particleboard was at 70wt%resin content and shell particle size of 1mm after which it continually dropped because of a decrease in particle mass concentration. The composites with higher particle weight fraction showed higher flexural strength Figure 4-7.

(Madueke et al., 2014) showed that the maximum bending strength was recorded at 20 weight percent reinforcement concentration, and the decrease in this strength was brought on by the particles' regulated movement within the matrix. In accordance with (Al-Mosawi et al., 2013) as well as (Durowaye et al., 2014), the flexural strength increased with increased fibre addition up to a maximum level, at which point additional increase resulted in a decrease in bending strengths. The microstructure and interfacial bonding between the matrix and reinforcement play a major role in the flexural characteristics of composite materials. The reduction in the overall surface area available for matrix-filler interaction in this investigation, which resulted in a poor load transfer between the matrix and the reinforcement, may be responsible for the drop in flexural strength.

Analysis of variance (ANOVA) for modulus of rupture (MOR) manufactured from coconut shell particles at varying matrix weight fraction is shown in Table 4-3. The P-value was 0.0149 which was lower than α -value thus indicating a significant difference in MOR at varying resin weight fractions and shell particles sizes.

Factor Coding: Actual

MOR (N/mm²)

Design Points:

● Above Surface

○ Below Surface

7.35 16.2

X1 = A

X2 = B

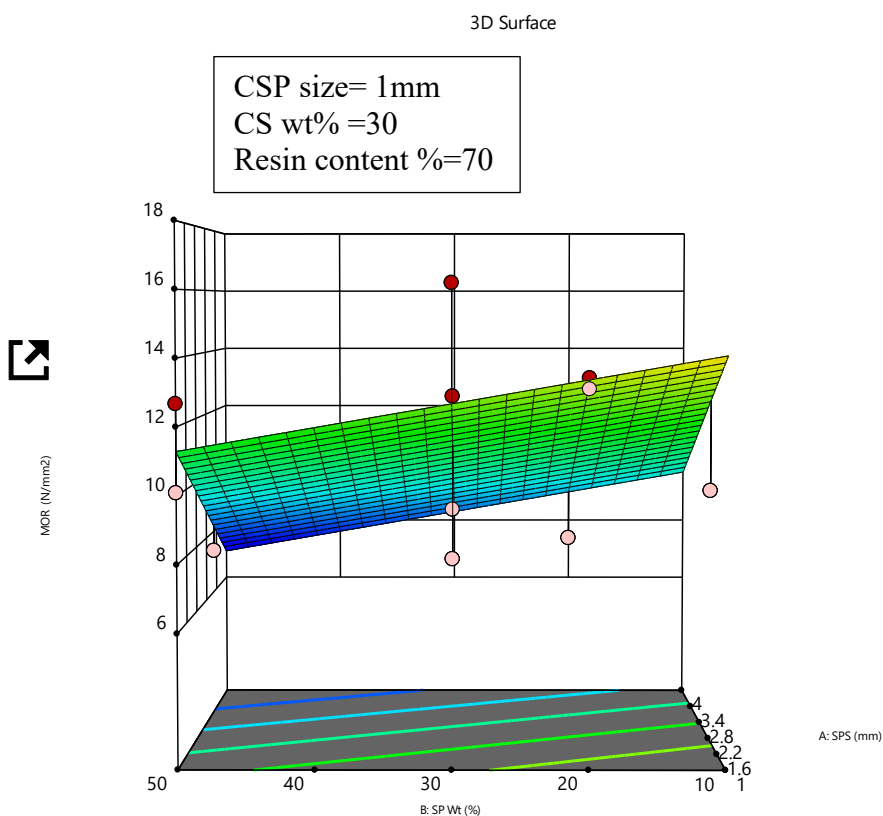


Figure 4-7 Modulus of rupture Vs CS particle size and resin content

4.4.1.2.1 ANOVA for Linear Model

Table 4-3 Response 2: Modulus of Rupture (MOR)

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	50.67	2	25.33	5.91	0.0149	Significant
A-SPS	40.37	1	40.37	9.42	0.0090	
B-SP Wt	14.19	1	14.19	3.31	0.0919	
Residual	55.71	13	4.29			
Lack of Fit	32.42	8	4.05	0.8699	0.5911	not significant
Pure Error	23.29	5	4.66			
Cor Total	106.37	15				

Factor coding is **Coded**.

The **Model F-value** of 5.91 indicates that the model is significant, with only a 1.49% probability that an F-value this large could result from noise

P-values less than 0.0500 indicate that the model terms are significant, with A being a significant model term in this case. Values greater than 0.1000 suggest that the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

The **Lack of Fit F-value** of 0.87 implies the Lack of Fit is not significant relative to the pure error. There is a 59.11% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good; we want the model to fit.

4.4.2 Discussion

Results of the mechanical properties of particleboards made from coconut shell particles and potato tuber waste powder are presented in Figures from 4-2, to 4-7, and in Tables 6-16 and 6-17 (in appendix).

According to EN 312 standard, 11.5 and 13.0 N/mm² are the minimum requirements for MOR of particleboard panels for general uses and interior fitments (including furniture), respectively, while the minimum MOE for interior fitments is 1600 N/mm² according to EN 312 (Amirou et al., 2013).

The measurements for the particleboards produced using water ethanol extracted coconut shell particles bonded with potato waste resin gave rise to MOR of 16.20 N/mm².

4.5 Physical Properties of Fabricated Particleboard

4.5.1 Water Absorption, Thickness Swelling and Density

Tables 7–18, table 7–19 and table 7–20 located in the appendix for reference, and Figures 4-

8,4-9 and 4-10 display the results of the Water absorption, thickness swelling and density of the fabricated particleboard respectively

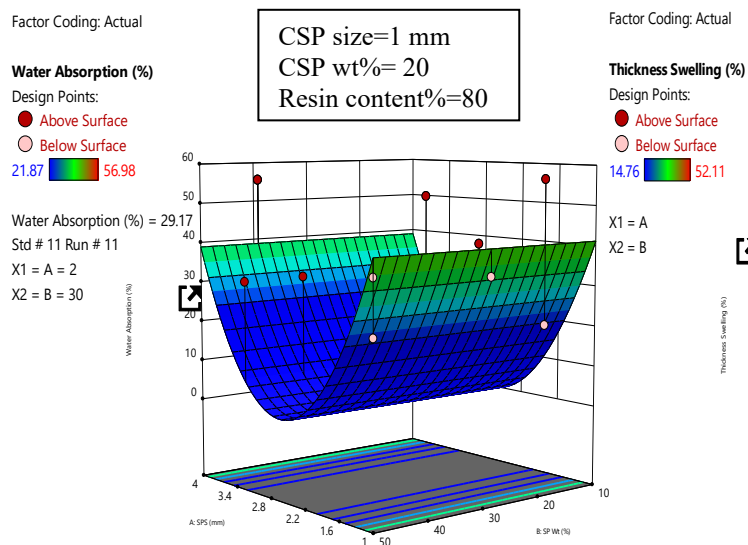


Figure 4-8 Water absorption of CSPB

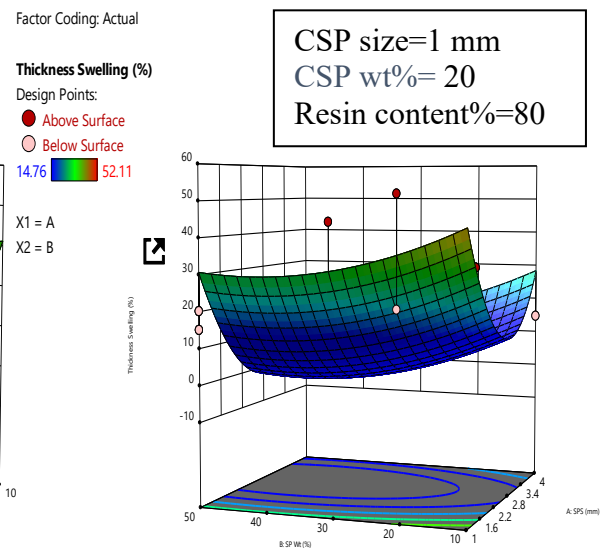


Figure 4-9 Thickness swelling of CSPB

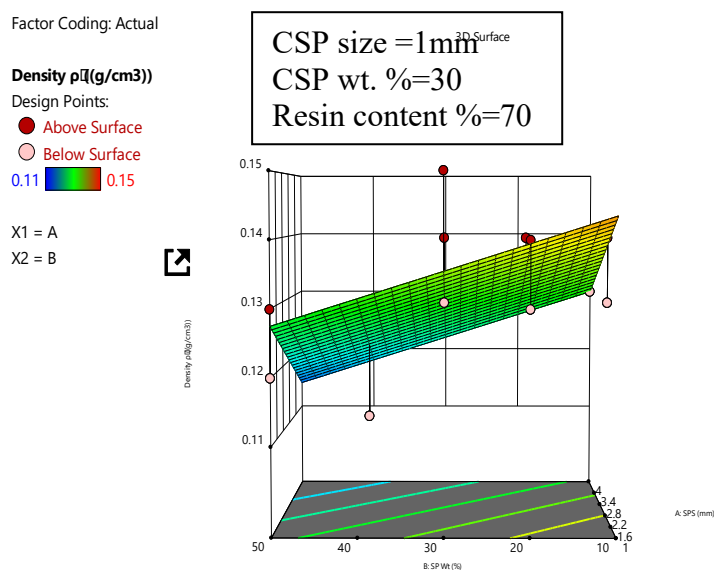


Figure 4-10 CSPB density

Flexural, tensile strength and physical properties of Coconut shell particle- reinforced Potato waste composites were determined.

4.5.1.1 The Effects of Resin Content on Water Absorption of Particleboard

Due to increased voids, polar content, and weak interfacial interaction between the fibre and the matrix, the water uptake in composites relies on the weight percent of the reinforcement.

In effective fibre/matrix interfacial adhesion systems, the swelling effect brought on by water intake is negligible (Abdulkareem et al., 2017; Wong 2013).

It is observed from Figure 4-6 and Table 6-18 that the moisture absorption percentage for the particleboard made of 80% resin content and 1 mm shell particle size is 56.98%. It can be seen that the water absorption increased with the increase in the resin content and the decrease in the shell particle size this may be attributed to the poor interfacial between the matrix and the reinforcement because of incomplete flowing of the resin as cold points that causes voids and thus absorb the water while on the other hand it was noticed also on the same resin content of 80% and smaller particle size of 1 mm that water absorption decreased with increase in resin content of the particleboard. These results agree with the study by (Rachtanapun et al., 2012). This could be as a result of a good interfacial between the matrix and the reinforcement due to a good flowing of the resin brought about by the strong intermolecular cohesive bonding within the molecules of the resin as which prevented water penetration to the composite.

Analysis of variance (ANOVA) of particleboard was done to investigate if resin weight fraction and shell particle size had an impact on the moisture content and the output is depicted in Table 4-3 From this analysis, the computed P-values (0.0011 & 0.0004) were lower than the α -value ($P < 0.05$) and this indicated that there were significant differences on varying resin content

4.5.1.1.1 ANOVA for Reduced Quadratic Model

Table 4-4 Response 3: Water Absorption

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	13321.26	2	6660.63	11.46	0.0011	Significant
A-SPS	11.04	1	11.04	0.0190	0.8924	
A ²	12365.66	1	12365.66	21.27	0.0004	
Residual	8139.58	14	581.40			
Lack of Fit	7049.44	9	783.27	3.59	0.0864	not significant
Pure Error	1090.15	5	218.03			
Total	21460.84	16				

Factor coding is **Coded**.

The **Model F-value** of 11.46 indicates that the model is significant, with only a 0.11% probability that such a large F-value could result from noise.

P-values less than 0.0500 indicate model terms are significant. In this case A² is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

The **Lack of Fit F-value** of 3.59 suggests an 8.64% probability that such a large value could occur due to noise. Lack of fit is bad; we want the model to fit. This relatively low probability (<10%) is troubling.

4.5.1.2 The Effects of Resin Content and Particle Size on Thickness Swelling of Particleboard

It is observed from Figure 4-7 extracted from Table 7-19 located (in appendix) for reference, that the moisture absorption percentage for the particleboard made of 80% resin content and 1 mm shell particle size is 52.11%. It can be seen that the thickness swelling increased with the increase in the resin content and the decrease in the shell particle size this may be attributed to the poor interfacial between the matrix and the reinforcement because of incomplete flowing of the resin as cold points that causes voids and thus absorb the water and; it was also observed that increasing the resin content to 90 and using a shell particle size of 4 mm resulted in a 14.76% decrease in thickness swelling of the particleboard. This could be as a result of a good interfacial between the matrix and the reinforcement due to a good flowing of the resin brought about by the strong intermolecular cohesive bonding within the molecule of the resin as which prevented water penetration to the composite.

Analysis of variance (ANOVA) of particleboard was done to investigate if resin weight fraction and shell particle size had an impact on the moisture content and the output is depicted in Table 4-4. From this analysis, the computed P-value of the model (0.0034) and shell particle size (0.0071) were lower than the α -value ($P < 0.05$) and this indicated that there was significant difference on varying shell particle size.

4.5.1.2.1 ANOVA for Reduced Quadratic Model

Table 4-5 Response 4: Thickness Swelling

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	7801.35	4	1950.34	7.19	0.0034	Significant
A-SPS	484.67	1	484.67	1.79	0.2061	
B-SP Wt.	305.01	1	305.01	1.12	0.3099	
A ²	2841.50	1	2841.50	10.47	0.0071	
B ²	113.14	1	113.14	0.4171	0.5306	
Residual	3255.29	12	271.27			
Lack of Fit	2727.14	7	389.59	3.69	0.0849	not significant
Pure Error	528.15	5	105.63			
Total	11056.64	16				

Factor coding is **Coded**.

The **Model F-value** of 7.19 indicates that the model is significant, with only a 0.34% probability that such a large F-value could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A² is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

The **Lack of Fit F-value** of 3.69 indicates an 8.49% probability that such a large value could occur due to noise. A significant lack of fit is undesirable, as it suggests the model does not fit well. This relatively low probability (<10%) is concerning.

4.5.1.3 The Effects of Resin Content and Shell Particle Size on the Density of Particleboard

From Figure 4-8 and Table 4-20 (in the appendix), The density of particleboards varies depending on the amount of resin content and shell particle size used (resin content of 60% and shell particle size of 3.15 mm had the lowest value of 11 g/cm³, while resin content of 70% and shell particle size of 1 mm had the maximum value of 15 g/cm³). An increase in the solid content of the resin may be the cause of this phenomenon. The potential cause of the density increase, according to (Rachtanapun et al., 2012), is resin polymer. The main determinants of density are the raw materials' density, binder density, pressing pressure, particle content, and other additives (Iswanto et al., 2013; Rachtanapun et al., 2012). Reduced porosity in the particleboard due to smaller and less varied particle sizes may also explain the increase in density with rising resin concentration.

An analysis of variance (regression) for particleboard density with varying matrix fractions and shell particle volume is shown in Table 4-5, and the analysis indicates that resin content and particle size had significant effects on density ($p < 0.05$).

4.5.1.3.1 ANOVA for Linear model

Table 4-6 Response 5: Density ρ

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	0.0008	2	0.0004	7.03	0.0085	Significant
A-SPS	0.0004	1	0.0004	6.85	0.0213	
B-SP Wt.	0.0005	1	0.0005	8.46	0.0122	
Residual	0.0007	13	0.0001			
Lack of Fit	0.0005	8	0.0001	1.45	0.3560	not significant
Pure Error	0.0002	5	0.0000			
Cor Total	0.0015	15				

Factor coding is **Coded**.

The **Model F-value** of 7.03 indicates that the model is significant, with only a 0.85% probability of such a large F-value occurring due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A, B are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

The **Lack of Fit F-value** of 1.45 implies the Lack of Fit is not significant relative to the pure error. A Lack of Fit F-value this large has a 35.60% probability of occurring due to noise. A non-significant lack of fit is desirable, as it indicates the model fits well.

4.5.1.4 Microstructure Characteristics

Fig.4-11 shows SEM micrographs of coconut shell particleboard of the optimal particle size of coconut shell at 1mm with the filler content of 30% and resin content of 70%. When comparing the scanning electron microscopic (SEM) photomicrographs of the coconut shell particles and potato tuber waste as shown in Figs. 4-11a and 4-11b respectively with the fabricated particle-board Fig4-11c, it can be observed that the coconut shell particles are embedded in potato tuber waste matrix because of the homogeneous dispersion and strong adhesion of coconut shell particles CSP with the matrix.

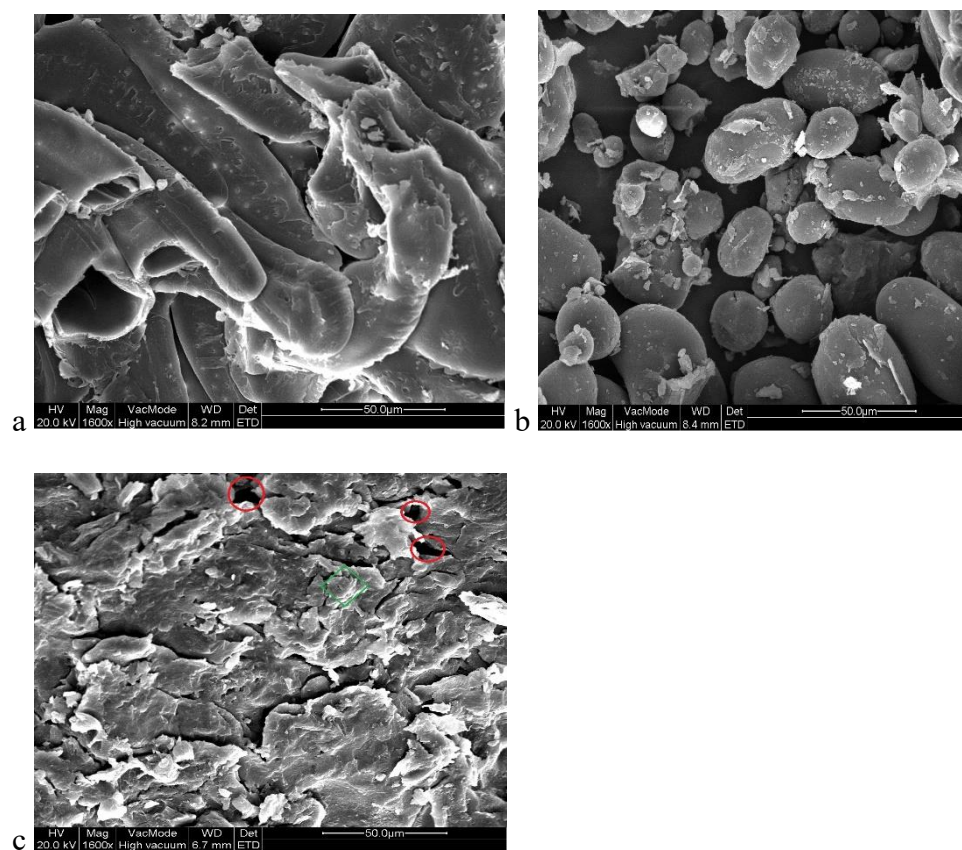


Figure 4-11 SEM images of (a) pretreated CSP and (b) potato tuber waste starch (c) coconut shell particles filled potato tuber waste matrix.

The investigation involved using a scanning electron microscope (SEM) to analyse the interaction between coconut shell particles (CSP) and potato tuber waste powder (PTW) within the manufactured particleboards. This experimental approach allowed for a detailed

examination of the structural composition and bonding characteristics of the composite materials, shedding light on the effectiveness of incorporating CSP and PTW in enhancing the properties of the particleboards, thereby contributing to the advancement of sustainable and eco-friendly materials in the field of composite manufacturing. This investigative process aimed to delve deeper into the relationship and effects of CSP and PTW within the manufactured particleboards. By employing SEM analysis, researcher sought to gain a comprehensive understanding of how these two components interacted and contributed to the overall properties and structural integrity of the particleboards.

The SEM analysis presented in Figure 4-11c demonstrates the transformation of starch from PTW into a gel, facilitating the bonding process that forms a continuous matrix encapsulating the pretreated CSP. This phenomenon is accompanied by the melting of starch granules, which then occupy the open pores, resulting in a reduction in pore size and ultimately leading to a more densely packed structure of the panels. The scanning electron microscope images illustrated in Fig 4-11c exhibit a decrease in open spaces and a more compact alignment between the fibres.

The exertion of production pressure, combined with the uniform dispersion of adhesive deeply penetrated into the fibre particles, induced a compacted configuration of the crushed cell walls of the fibres, thereby augmenting the quality of the particleboards. The presence of starch granules that fill the voids between particle surfaces significantly enhances both the physical and mechanical properties, as well as the dimensional stability of the particleboards. Throughout the gelatinization process of heat-treated modified starches, the tangled amylopectin is liberated as the granules fracture and swell, thereby further enhancing the characteristics of the particleboards in accordance with (Akinyemi et al., 2019).

Furthermore, the SEM imagery unveiled the clustering of CSP and the existence of micropores, suggesting a localized low compaction that could potentially render the particleboard

hydrophilic. This intricate sequence of events underscores the significance of the interplay between various constituents in the manufacturing of particleboards and its consequential impact on their attributes and functionality.

4.5.1.5 Thermal Analysis

The Fourier transform infrared (FTIR) spectrum, a potent analytical method employed to examine how molecules vibrate, is showcased in Figure 4-12 to highlight the unique characteristics of coconut shell particleboard (CSPB). This spectrum offers valuable insights into CSPB's chemical makeup and bonding arrangement, revealing how different functional groups interact within the material. By examining the peaks and patterns displayed in the FTIR spectrum of CSPB, researcher gain a deeper understanding of its unique properties and potential applications in different industrial sectors. The appearance of a prominent peak within the spectral range of 3620 cm^{-1} to 3306 cm^{-1} has been linked to the phenomenon of hydrogen bonding that arises from the interaction of the -OH functional groups that are inherent in the structure of CSP. This particular spectral characteristic serves as an indication of the precise molecular interactions that occur among the CSP molecules, emphasizing the significance of the -OH groups in enabling hydrogen bonding within the compound. Additionally, the appearance of the peak at 2992 cm^{-1} is directly linked to the stretching of C-H bonds. Furthermore, the absorption occurring at 1760 cm^{-1} can be attributed to the stretching of the C=O bonds within the carboxyl group of the acetyl component derived from hemicelluloses. The peaks observed at 1560 cm^{-1} and 1480 cm^{-1} are significant as they contribute to the presence of the conjugated C-O group associated with the aromatic skeletal structure found in lignin. Moreover, it is crucial to emphasize that the appearance of the peak at 1372 cm^{-1} indicates a structural modification related to the flexing of the C-H entities existing in cellulose and hemicelluloses, offering significant perspectives into the molecular interplays and configurational alterations taking place within these biopolymers. Similarly, the peak observed

at 950 cm^{-1} signifies the vibrational mode associated with the C-H groups found in cellulose. Conversely, the peak at 1183 cm^{-1} is linked to the C-O group that arises from the acetyl component present in lignin. The peak detected at 1063 cm^{-1} falls within a range that is indicative of a significant constituent found in cellulose and lignin, specifically associated with the stretching of C-O bonds. Moreover, the spectral peaks observed within the range of 739 cm^{-1} to 795 cm^{-1} provide valuable insights into the vibrational characteristics attributed to the aromatic C-H functional groups that are specifically inherent to the chemical structure of lignin. Cellulose, an intricate organic compound, is found within the cellular structures of plant cell walls. The presence of these distinct peaks serves as evidence of the presence and correlations of particular molecular bonds within the lignin molecules. An analysis of Fig 4-12 reveals a decrease in the intensity of the hydroxyl group (-OH) peak present in treated CSP, signifying a reduction in the hydrophilic nature of CSP. This alteration indicates a change in the chemical composition and properties of the coconut shell particleboard due to treatment.

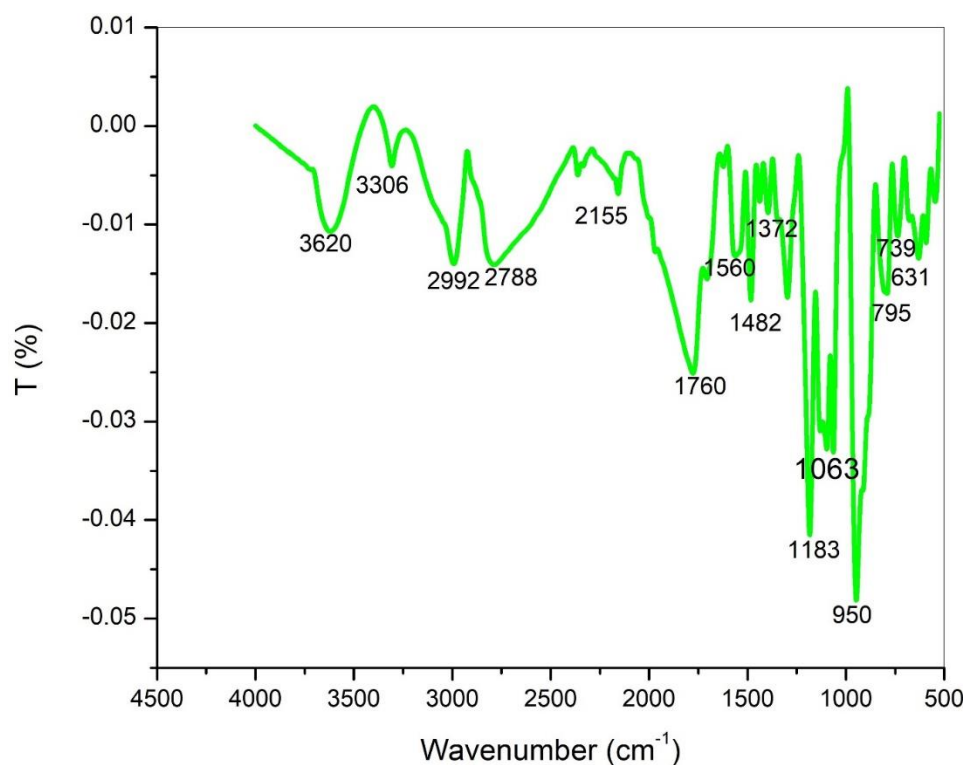


Figure 4-12 FTIR spectrum of CSPB

Figure 4-13 display the average of three reading of digital scanning calorimetry of raw CSP, pretreated CSP and potato tuber waste.

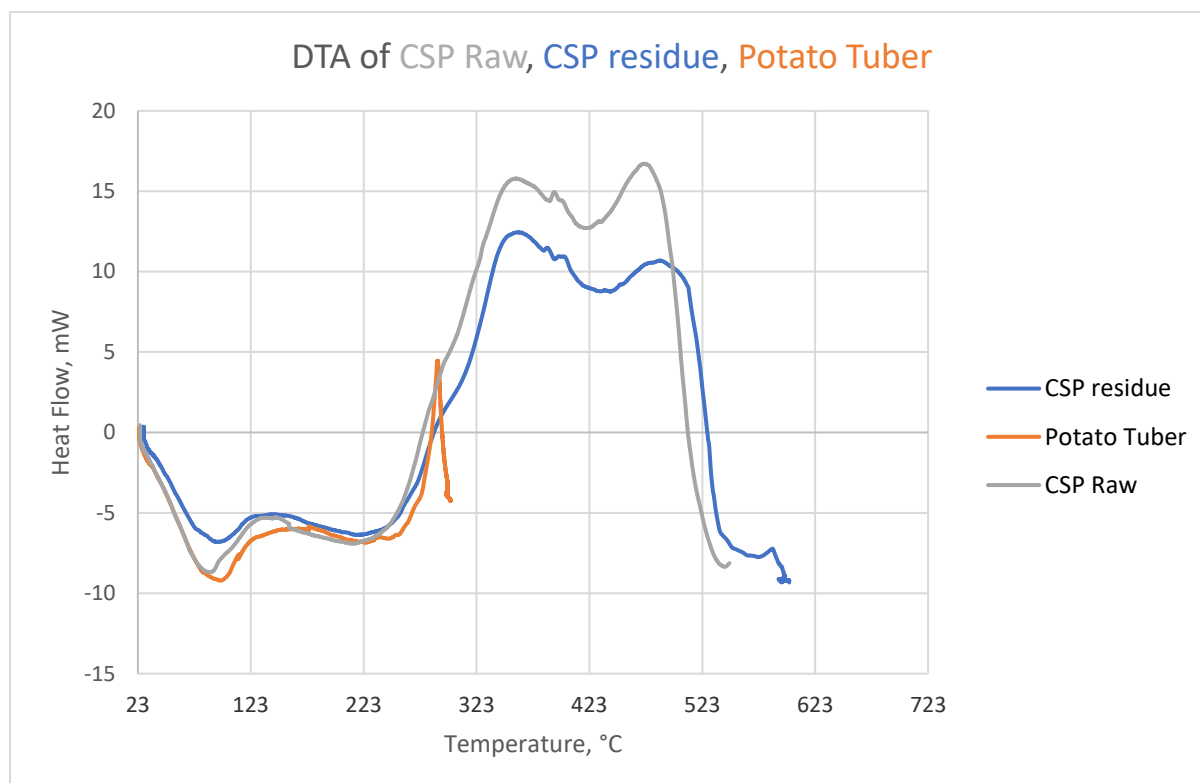


Figure 4-13 Digital scanning calorimetry of CSP raw and residue and potato waste

Figure 4-13 above depicts the digital scanning calorimetry (DSC) results of raw coconut shell particles (CSP), CSP residue, and potato waste, providing further insights into their thermal behaviour and decomposition patterns.

Looking into the details presented in Figure 4-13, a pivotal moment was observed at a heat flow of -6 mWb, where a significant phenomenon occurs: polymerization initiates at an intercept temperature of 160°C, marking the onset of an endothermic reaction. This crucial temperature signifies the beginning of a transformative process within the materials.

A closer examination of the temperature range between 30 and 100°C reveals the initial stages of thermal processing. Here, the samples undergo notable transformations: water evaporation

occurs as the materials heat up, while unstable substances such as hemicellulose and carbon dioxide start to break down. These early reactions set the stage for subsequent thermal processes, laying the groundwork for further changes in the material structure.

Drawing upon insights from previous research (Sulaiman et al., 2013), we learn that specific temperature thresholds trigger significant reactions in different components of the materials. For instance, the decomposition of potato waste occurs within the range of 60 to 165°C, whereas CSP undergoes a multi-phase decomposition process between 200 and 400°C. This difference highlights the varied thermal responses shown by various materials when subjected to comparable conditions. Additionally, clarification from research. (Li et al., 2008) underscores the significance of accurate temperature regulation throughout manufacturing procedures.

Optimal temperatures, such as the identified 160°C, facilitate efficient polymerization and material synthesis. Additionally, considerations regarding energy consumption come into play, with pretreated CSP demonstrating advantages over raw CSP due to lower extractives content and consequently reduced power consumption.

The culmination of thermal reactions occurs at 540°C, where all constituents are completely decomposed. This endpoint signifies the completion of the thermal processing journey, highlighting the comprehensive understanding gained through thermal analysis techniques like those represented in Figure 4-13.

4.5.1.6 Decomposition

Table 7-21, found in the appendix for reference, provides a comprehensive overview of the results obtained from testing the decomposition of coconut shell particleboard (CSPB) in comparison to control particleboard made from melamine urea formaldehyde (MUFPB). The experimental procedure involved burying the samples in soil for a duration of four weeks. At

weekly intervals, each sample was carefully excavated from the soil, subjected to thorough washing with deionized water to remove any soil residues, and subsequently dried in an oven at a controlled temperature of 60 ± 2 °C for a period of 24 hours. After drying, the samples were weighed to determine any changes in mass over the course of the decomposition process.

The degree of decomposition was quantified through the measurement of weight loss (WL), which was calculated using a specific formula as shown in equation 4-1. This formula probably entails comparing the initial weight of the samples before they are placed in the soil environment with their weights following the biodegradation period. It accounts for any reduction in mass that occurs during the degradation process.

$$WL (\%) = \frac{W_0 - W_1}{W_0} * 100 \quad \text{Equation 4-1}$$

Where W_0 is the initial mass, W_1 is the mass after degradation. The weight loss (WL, %) is the average of at least five specimens of each sample.

Figure 4-14 clearly shows how the coconut shell particleboard (CS) decomposed comparing to the control particleboard of melamine urea formaldehyde (MUF PB).

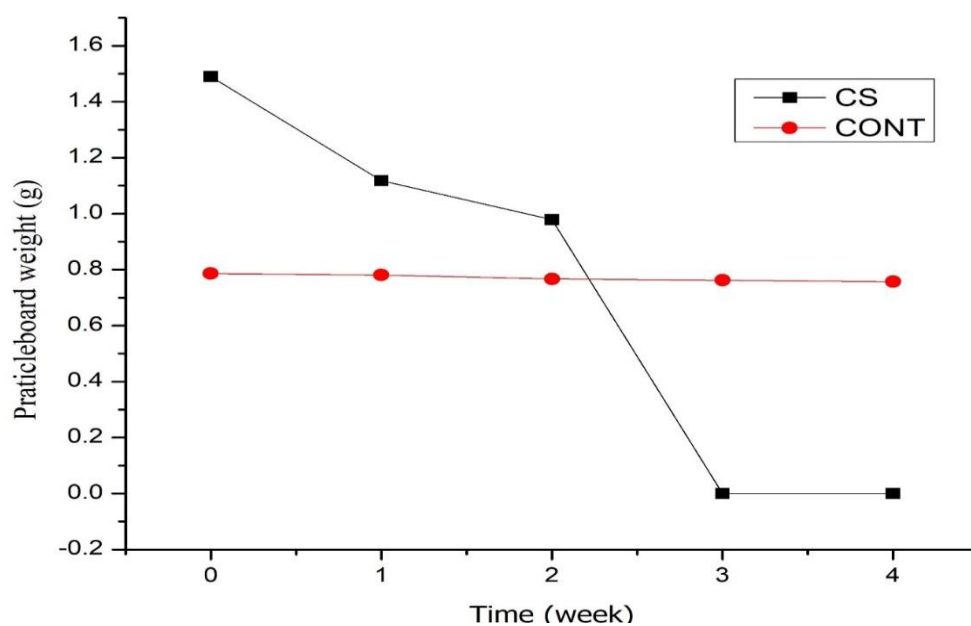


Figure 4-14 Decomposition of the CS and MUF particleboards

During this analysis, the initial weight acts as a baseline reference, allowing the researcher to

quantify the extent of biodegradation by measuring the difference in weight before and after exposure to soil conditions. This weight loss serves as a tangible indicator of the materials' susceptibility to degradation and provides valuable data for assessing their biodegradability properties.

Building on this process, researchers may consider additional factors influencing the biodegradation rate, such as environmental conditions, microbial activity, and material composition. Including these variables in their analysis can provide a deeper understanding of the biodegradation process and its environmental implications. This approach will help assess the materials' environmental fate more comprehensively. By evaluating these factors, this study can gain valuable insights into how CSPB and MUFPB biodegrade under specific environmental conditions, offering a clearer picture of their long-term impact on the environment.

By systematically analysing the biodegradation process and quantifying the resulting weight loss, this research can draw meaningful conclusions about the effectiveness of CSPB as a biodegradable material compared to conventional MUFPB. These findings enhance the understanding of the environmental sustainability of various materials and inform future decisions regarding their use and development. The samples analysed were carefully chosen from a batch with an optimal resin content of 70% and a particle size of 1 mm.

Additionally, a commercially available melamine urea formaldehyde particleboard (MUFPB) was included in the study as a control for comparison. After subjecting both sample types to biodegradation testing in a soil environment, significant differences in their degradation rates were observed. Remarkably, within just three weeks, the coconut shell particleboard (CSPB) was fully degraded, showing a 100% degradation rate. In contrast, the MUFPB control exhibited a much lower degradation rate of 3.77% over the same period.

These findings emphasize the contrasting biodegradability profiles of CSPB and MUFPB

under the experimental conditions. While CSPB, made from natural coconut shell fibres, exhibited rapid and complete biodegradation, MUFPB, a synthetic material, showed a much slower rate of degradation. This difference highlights the potential environmental benefits of using natural, renewable resources like coconut shells in the production of biodegradable materials such as CSPB.

The observed differences in degradation rates provide valuable insights for industries and policymakers seeking to promote the adoption of sustainable materials in various applications. By understanding the biodegradability performance of different materials, informed decisions can be made to minimize environmental impact and promote the development of eco-friendly alternatives.

4.5.1.7 Discussion

The findings regarding the mechanical properties of particleboards, crafted from coconut shell particles and potato tuber waste powder, are comprehensively detailed in Figures 4-2 to 4-5, along with Tables 7-16 and 7-17, which are conveniently located in the appendix for reference. These results are crucial in assessing the suitability of these innovative materials for various applications. They provide insights into the strength and stiffness of the particleboards, which are essential considerations in their utilization for construction and interior fitments, including furniture.

These results are crucial in assessing the suitability of these innovative materials for various applications. They provide insights into the strength and stiffness of the particleboards, which are essential considerations in their utilization for construction and interior fitments, including furniture.

In accordance with the EN 312 standard, specific minimum requirements are established for the modulus of rupture (MOR) of particleboard panels intended for general use and interior fitments. For instance, the minimum MOR values are set at 11.5 N/m² for general uses and 13.0

N/m² for interior furniture's (Amirou et al., 2013)

The measurements obtained for the particleboards, produced utilizing water ethanol pretreated coconut shell particles bonded with potato waste resin, are particularly noteworthy. These particleboards demonstrated an impressive MOR of 16.20 N/mm², surpassing the minimum requirements stipulated by the EN 312 standard. Such robust mechanical performance underscores the potential of these sustainable materials for a wide range of applications, including furniture and interior fitments.

By thoroughly analysing and interpreting these mechanical property measurements, this research equips industry stakeholders with valuable insights to make informed decisions regarding the development and utilization of coconut shell and potato waste-based particleboards. These eco-friendly alternatives not only meet stringent quality standards but also promote sustainable practices in the construction and furniture industries.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The primary objective of this research project was to initiate the development and comprehensive characterization of particleboard made from coconut shell particles (CSP) and potato tuber waste (PTW). This involved not only the creation of the particleboard but also an in-depth analysis of its properties and characteristics to better understand its composition and potential uses. Using the compression molding technique, the study explored the board-making process, carefully evaluating various factors such as particle size, resin content, and the treatment applied to CSP.

This research primarily aimed to maximize the potential of potato tuber waste (PTW) and coconut shell particles (CSP) in producing a versatile particleboard suitable for various housing construction applications. The project adopted a comprehensive approach, utilizing a range of analytical and fabrication techniques to explore the physical and chemical properties of both treated and untreated CSP. By experimenting with different consolidation pressures, temperatures, and particle sizes, the study sought to produce particleboards and carefully examine their mechanical and physical properties in detail.

Our findings have yielded these valuable insights:

- A thorough examination of CSP's lignocellulosic content, moisture levels, and chemical and physical attributes.
- Successful production of particleboards with varied compositions through adept manipulation of consolidation parameters and blend ratios of CSP and PTW.
- Evaluation of mechanical and physical characteristics, including tensile strength, modulus of rupture, water absorbance, thickness swelling, and density.

Key conclusions drawn from this extensive study include:

- Identification of the $1 + < 1$ mm fraction as the predominant weight fraction in the CSP size distribution.
- Establishment of optimal manufacturing conditions at 10 MPa, 160°C, and 10 minutes.
- Enhanced lignin and cellulose levels, coupled with reduced hemicellulose content, resulting from CSP treatment.
- Noteworthy influences of particle size, blend percentage, and resin content on the mechanical and physical properties of the particleboards.
- Significant enhancement in tensile strength (TS), water resistance (WA), density, and modulus of rupture (MOR) were observed by employing small CSP size of ($1 + < 1$ mm) and higher resin content (70%). These improvements can be attributed to the strong physical bonding between potato tuber waste networks and CSP.

Moving forward, its advocated for further research endeavours to deepen a better understanding of internal bonding effects on particleboards and to refine production processes.

Investigating the potential benefits of adding wax and citric acid to assess their influence on elongation at break and water resistance may yield valuable insights. Moreover, subsequent investigations should delve into the potential applications and market feasibility of CSP and PTW-based particleboards within the construction industry.

Essentially, this research advocates for the eco-friendly utilization of agricultural residues in manufacturing valuable products like particleboards. By repurposing these residues, the study not only brings about environmental advantages but also stimulates innovation within construction methodologies. This shift towards sustainable practices not only reduces waste but also opens up avenues for creative solutions in the construction industry, aligning with the global push towards greener, more sustainable practices.

5.2 Recommendations

1. **Manufacturing Process Optimization:** It is advisable to apply the identified optimal conditions (10 MPa, 160°C, 10 minutes) in commercial production to enhance efficiency and ensure superior product quality.
2. **Utilization of Small CSP Size and Higher Resin Content:** Given the significant enhancements observed in tensile strength, water resistance, density, and modulus of rupture with small CSP size ($1 + < 1$ mm) and higher resin content (70%), it's recommended to prioritize these parameters in the production process.
3. **Exploration of Additives:** Investigating the impacts of incorporating wax and citric acid to the particleboard composition can provide insights into further enhancing properties such as elongation at break and water resistance.
4. **Market Feasibility Studies:** Conducting market feasibility studies to assess the potential applications and demand for CSP and PTW-based particleboards within the construction industry can help identify potential market niches and consumer preferences.

5.3 Areas for Further Studies:

1. **Internal Bonding Effects:** Further research is warranted to deepen understanding of the internal bonding effects on particleboards, which can contribute to optimizing production processes and enhancing product quality.
2. **Exploring the Impact of Additives:** Further investigation into how supplementary materials such as wax and citric acid affect particleboard properties can offer a deeper comprehension of their contribution to enhancing performance attributes.
3. **Applications and Market Feasibility:** Expanding research to explore various applications of CSP and PTW-based particleboards beyond housing construction, as well as conducting in-depth market feasibility studies, can provide valuable insights

into commercialization opportunities and possible obstacles to adoption.

4. **Sustainability Assessments:** Conducting life cycle assessments and environmental impact studies to evaluate the overall sustainability of CSP and PTW-based particleboards compared to traditional materials can provide valuable information for decision-makers and stakeholders.

In summary, by implementing these recommendations and exploring these areas for further studies, this research can contribute to advancing the development and utilization of eco-friendly particleboards made from agricultural residues, thereby promoting sustainability and innovation within the construction industry.

6 REFERENCES

- Abdulkareem, S., Raji, S., & Adeniyi, A. J. N. J. O. T. D. (2017). Development of particleboard from waste styrofoam and sawdust. *14*(1), 18-22.
- Ageyeva, T., Sibikin, I., & Kovács, J. G. J. P. (2019). A review of thermoplastic resin transfer molding: Process modeling and simulation. *11*(10), 1555.
- Akhtar, K., Khan, S. A., Khan, S. B., & Asiri, A. M. (2018). *Scanning electron microscopy: Principle and applications in nanomaterials characterization*. Springer.
- Akinyemi, B. A., Olamide, O., & Oluwasogo, D. J. C. S. I. C. M. (2019). Formaldehyde free particleboards from wood chip wastes using glutaraldehyde modified cassava starch as binder. *11*, e00236.
- Al-Mosawi, A. I., Rijab, M. A., Abdullah, N., Mahdi, S. J. I. J. O. E. R. I. S. S., & engineering. (2013). Flexural strength of fiber reinforced composite. *2*(1), 1-3.
- Almeida, R. R., Del Menezzi, C. H. S., & Teixeira, D. E. J. B. T. (2002). Utilization of the coconut shell of babaçu (*Orbignya* sp.) to produce cement-bonded particleboard. *85*(2), 159-163.
- Ambrosio, L., Carotenuto, G., & Nicolais, L. J. H. O. B. P. (2016). Chapter 2 Composite Materials. 214-241.
- Amirou, S., Zerizer, A., Pizzi, A., Haddadou, I., & Zhou, X. (2013). Particleboards production from date palm biomass.
- Ang, A. F., Ashaari, Z., Lee, S. H., Tahir, P. M., Halis, R. J. I. J. O. A., & Adhesives. (2019). Lignin-based copolymer adhesives for composite wood panels—A review. *95*, 102408.
- Anggraini, R., Khabibi, J., & Adelka, Y. F. J. J. S. T. (2021). Karakteristik papan partikel dari campuran limbah akasia (*Acacia mangium* willd.) dan kulit kelapa muda (*Cocos nucifera* L.): Characteristics of ParticleBoard from Mixed Waste of Acacia (*Acacia mangium* Willd.) and Coconut Shell (*Cocos nucifera* L. *5*(1), 366-381.
- Anuchi, S. O., Campbell, K. L. S., & Hallett, J. P. J. S. r. (2022). Effective pretreatment of lignin-rich coconut wastes using a low-cost ionic liquid. *12*(1), 1-11.
- Arun, S., Shankar, S., Selven, P. J. I. J. O. I. T., & Engineering, E. (2014). Experimental studies on drying characteristics of coconuts in a solar tunnel greenhouse dryer coupled with biomass backup heater. *4*(5), 56-60.
- AS, J. S., SP, R., Chandrasekar, V., & Sasikala, S. (2013). Coconut: An extensive review on value added products. In: December.
- Atoyebi, O., Aladegboye, O., & Fatoki, F. (2021). Physico-Mechanical Properties of Particle -Board made from Coconut Shell, Coconut Husk and Palm Kernel Shell. IOP Conference Series: Materials Science and Engineering,
- Bagherpour, S. (2012). *Fibre reinforced polyester composites*. InTech London.

- BAT, B. A. T. (2016). Production of Wood-based Panels.
- Batalla, L., Nunez, A. J., & Marcovich, N. E. J. J. O. A. P. S. (2005). Particleboards from peanut-shell flour. *97*(3), 916-923.
- Biesaga, M. J. J. O. C. A. (2011). Influence of extraction methods on stability of flavonoids. *1218*(18), 2505-2512.
- Bledzki, A. K., Mamun, A. A., Volk, J. J. C. S., & Technology. (2010). Barley husk and coconut shell reinforced polypropylene composites: the effect of fibre physical, chemical and surface properties. *70*(5), 840-846.
- Britannica, T. J. A. E. B. (2020). Editors of Encyclopaedia.
- Brito, F. M. S., Silva, B. A., Carvalho, I. M. d., Baúti, S. B., Mendes, L. M., & Guimarães Júnior, J. B. J. F. E. A. (2022). Technological Properties of Medium Density Particleboards Produced with Peanut (*Arachis Hypogaea*) and *Pinus Oocarpa* Hulls. *29*.
- Chen, L., Xing, L., Han, L. J. R., & Reviews, S. E. (2009). Renewable energy from agro-residues in China: Solid biofuels and biomass briquetting technology. *13*(9), 2689-2695.
- Chun, K. S., Husseinsyah, S., & Osman, H. J. J. O. P. R. (2012). Mechanical and thermal properties of coconut shell powder filled polylactic acid biocomposites: effects of the filler content and silane coupling agent. *19*(5), 1-8.
- Coenders, A. (2004). *Química culinaria: Estudio de lo que sucede a los alimentos antes, durante y después de cocinados*. Acribia.
- Conroy, S. J. B. U. (2011). The efficacy of using coconut shell powder as a filler/reinforcement in thermoplastic composites.
- Dai, C., Wasylciw, W., Jin, J. J. W. S., & Technology. (2004). Comparison of the pressing behaviour of wood particleboard and strawboard. *38*(7), 529-537.
- Dence, C. W. (1992). The determination of lignin. In *Methods in lignin chemistry* (pp. 33-61). Springer.
- Desvaux, M. J. F. m. r. (2005). *Clostridium cellulolyticum*: model organism of mesophilic cellulolytic clostridia. *29*(4), 741-764.
- Devau, A., Goffart, J.-P., Kromann, P., Andrade-Piedra, J., Polar, V., & Hareau, G. J. P. R. (2021). The potato of the future: opportunities and challenges in sustainable agri-food systems. *64*(4), 681-720.
- Dholakiya, B. J. p. (2012). Unsaturated polyester resin for specialty applications. *7*, 167-202.
- Dong, C., & Davies, I. J. J. C. P. B. E. (2012). Flexural properties of macadamia nut shell particle reinforced polyester composites. *43*(7), 2751-2756.

- Durowaye, S., Lawal, G., Akande, M., & Durowaye, V. J. I. J. O. M. E. (2014). Mechanical properties of particulate coconut shell and palm fruit polyester composites. *4*(4), 141-147.
- Essabir, H., Nekhlaoui, S., Malha, M., Bensalah, M., Arrakhiz, F., Qaiss, A., Bouhfid, R. J. M., & Design. (2013). Bio-composites based on polypropylene reinforced with Almond Shells particles: Mechanical and thermal properties. *51*, 225-230.
- Faruk, O., Bledzki, A. K., Fink, H.-P., & Sain, M. J. P. i. p. s. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *37*(11), 1552-1596.
- Fengel, D., & Wegener, G. (2011). *Wood: chemistry, ultrastructure, reactions*. Walter de Gruyter.
- Ferrández-García, C.-E., Ferrández-García, A., Ferrández-Villena, M., Hidalgo-Cordero, J. F., García-Ortuño, T., & Ferrández-García, M.-T. J. F. (2018). Physical and mechanical properties of particleboard made from palm tree prunings. *9*(12), 755.
- Food and Agriculture Organization of The United Nations. (2020). *Crops and livestock products*. <https://www.fao.org/faostat/en/#data/QCL>
- Ganiron Jr, T. U. J. J. O. E. S., & Review, T. (2013). Sustainable Management of Waste Coconut Shells as Aggregates in Concrete Mixture. *6*(5).
- García, A. V., Santonja, M. R., Sanahuja, A. B., Selva, M. D. C. G. J. P. D., & stability. (2014). Characterization and degradation characteristics of poly (ϵ -caprolactone)-based composites reinforced with almond skin residues. *108*, 269-279.
- George, N., Varghese, V. M., & Kavitha, O. (2023). Earth's Versatile Gift: Cellulose. In *Handbook of Biomass* (pp. 1-25). Springer.
- Ghani, W., Abdullah, M., Matori, K., Alias, A., & Silva, G. J. J. O. T. I. O. E. (2010). Physical and thermochemical characterization of Malaysian biomass ashes. *71*, 9-18.
- Gonçalves, F. A., Ruiz, H. A., dos Santos, E. S., Teixeira, J. A., de Macedo, G. R. J. W., & Valorization, B. (2019). Valorization, comparison and characterization of coconuts waste and cactus in a biorefinery context using NaClO₂–C₂H₄O₂ and sequential NaClO₂–C₂H₄O₂/autohydrolysis pretreatment. *10*(8), 2249-2262.
- Greene, J. P. (2021). *Automotive plastics and composites: materials and processing*. William Andrew.
- Guerue, M., Tekeli, S., Bilici, I. J. M., & design. (2006). Manufacturing of urea–formaldehyde-based composite particleboard from almond shell. *27*(10), 1148-1151.
- Guler, C., Ozen, R., & Kalaycioglu, H. (2002). Utilization of Cotton Stalks (*Gossypium hirsutum* L.) as a Possible Raw Material for the Particleboard Production. 56th Appita Annual Conference, Rotorua, New Zealand 18-20 March 2002: Proceedings,

- Hainin, M. R., Matori, M. Y., & Akin, O. E. J. J. T. (2014). Evaluation of factors influencing strength of foamed bitumen stabilised mix. *70*(4).
- Harussani, M., Sapuan, S., Nadeem, G., Rafin, T., & Kirubaanand, W. J. D. T. (2022). Recent applications of carbon-based composites in defence industry: A review. *18*(8), 1281-1300.
- Hatta, Z. N., Mursal, M., & Ismail, I. J. J. O. A. P. S. (2021). Mechanical properties of coconut shell particleboard using epoxy resin adhesive. *10*(2), 36-40.
- Hendriks, A., & Zeeman, G. J. B. t. (2009). Pretreatments to enhance the digestibility of lignocellulosic biomass. *100*(1), 10-18.
- Hofstrand, A., Moslemi, A., & Garcia, J. F. J. F. P. J. (1984). Curing characteristics of wood particles from nine northern Rocky Mountain species mixed with Portland cement. *34*(2), 57-61.
- Houghton, R. (2008). Encyclopedia of Ecology, eds Jorgensen E-CSE, Fath B. In: Academic, New York.
- Indeglia, P. (1998). *Reuse of coconut residues as activated carbon for domestic water purification in developing regions* [Humboldt State University].
- Islam, M. T., Das, S. C., Saha, J., Paul, D., Islam, M. T., Rahman, M., Khan, M. A. J. C., & Engineering, M. (2017). Effect of coconut shell powder as filler on the mechanical properties of coir-polyester composites. *5*(4), 75-82.
- Ismail, I., Jalil, Z., Olaiya, N., Abdullah, C., Fazita, M., & Abdul Khalil, H. J. P. (2020). Properties and Characterization of New Approach Organic Nanoparticle-Based Biocomposite Board. *12*(10), 2236.
- Iswanto, A. H., Febrianto, F., Hadi, Y. S., Ruhendi, S., & Hermawan, D. J. M. J. O. T. (2013). The effect of pressing temperature and time on the quality of particleboard made from jatropha fruit hulls treated in acidic condition. *17*(3), 8.
- Jain, N., Gupta, R., & Jain, D. (1967). Particleboard from groundnut shells. Proceedings of 11th Silviculture Conference,
- Jani, S. M., Rushdan, I. J. J. o. T. A., & Science, F. (2014). Effect of bleaching on coir fibre pulp and paper properties. *42*(1), 51-61.
- Kalanatarifard, A., & Yang, G. S. J. J. O. S. D. (2012). Identification of the municipal solid waste characteristics and potential of plastic recovery at Bakri Landfill, Muar, Malaysia. *5*(7), 11.
- Kaseem, M., Hamad, K., & Deri, F. J. P. S. S. A. (2012). Thermoplastic starch blends: A review of recent works. *54*(2), 165-176.
- Kasirajan, S., & Ngouajio, M. J. A. f. s. d. (2012). Polyethylene and biodegradable mulches for agricultural applications: a review. *32*(2), 501-529.

- Khan, S. A., Khan, S. B., Khan, L. U., Farooq, A., Akhtar, K., & Asiri, A. M. J. H. O. M. C. (2018). Fourier transform infrared spectroscopy: fundamentals and application in functional groups and nanomaterials characterization. 317-344.
- Kibria, A. A., Kamrunnessa, M., & Rahman, M. J. S. (2018). Extraction and evaluation of phytochemicals from green coconut (*Cocos nucifera*) shell. 1, 2.
- Kirti, C., Kumar, S. M., Kumar, S. A., & Arora, T. J. I. J. R. A. S. E. T. (2015). Experimental study of coconut shell concrete. 3, 49-53.
- Kollmann, F. (1966). Holzspanplatten und Holzspanformlinge Rohstoffe, Herstellung, Plankosten Qalitatskontrolle USW. In: Springer.
- Kowaluk, G., Szymanowski, K., Kozłowski, P., Kukula, W., Sala, C., Robles, E., Czarniak, P. J. W., & valorization, b. (2020). Functional assessment of particleboards made of apple and plum orchard pruning. 11(6), 2877-2886.
- Kumar, A., Swamy, R. J. A. J. O. E., & sciences, a. (2011). Evaluation of mechanical properties of Al6061, fly ash and e-glass fiber reinforced hybrid metal matrix composites. 6(5), 40-44.
- Laureano-Perez, L., Teymouri, F., Alizadeh, H., Dale, B. E. J. A. B., & biotechnology. (2005). Understanding factors that limit enzymatic hydrolysis of biomass. 124(1), 1081-1099.
- Leman, A. S., Shahidan, S., Senin, M. S., & Hannan, N. I. R. R. (2016). A preliminary study on chemical and physical properties of coconut shell powder as a filler in concrete. IOP Conference Series: Materials Science and Engineering,
- LeVan, S., Ross, R. J., & Winandy, J. E. (1990). *Effects of fire retardant chemicals on the bending properties of wood at elevated temperatures* (Vol. 498). US Department of Agriculture, Forest Service, Forest Products Laboratory.
- Li, W., Yang, K., Peng, J., Zhang, L., Guo, S., Xia, H. J. I. c., & products. (2008). Effects of carbonization temperatures on characteristics of porosity in coconut shell chars and activated carbons derived from carbonized coconut shell chars. 28(2), 190-198.
- Lim, J. S., Manan, Z. A., Alwi, S. R. W., Hashim, H. J. R., & reviews, S. E. (2012). A review on utilisation of biomass from rice industry as a source of renewable energy. 16(5), 3084-3094.
- Lima, E., Sousa, C., Meneses, L., Ximenes, N., Júnior, S., Vasconcelos, G., Lima, N., Patrocínio, M., Macedo, D., Vasconcelos, S. J. B. J. O. M., & Research, B. (2015). *Cocos nucifera* (L.)(Arecaceae): A phytochemical and pharmacological review. 48, 953-964.
- Liyanage, C. D., & Pieris, M. J. P. C. (2015). A physico-chemical analysis of coconut shell powder. 16, 222-228.

- Lobo, M., & Dorta, E. (2019). Utilization and management of horticultural waste. In *Postharvest technology of perishable horticultural commodities* (pp. 639-666). Elsevier.
- Ma, M., & Ji, X. (2021). Extraction, Purification, and Applications of Hemicellulose. *Paper and Biomaterials*, 6(3), 47-60. <https://doi.org/10.1213/j.issn.2096-2355.2021.03.006>
- Madakson, P., Yawas, D., Apasi, A. J. I. J. O. E. S., & technology. (2012). Characterization of coconut shell ash for potential utilization in metal matrix composites for automotive applications. 4(3), 1190-1198.
- Madueke, C. I., Bolasodun, B., Umunakwe, R. J. I. J. O. P., & Engineering, T. (2014). Mechanical properties of tere-phthalic unsaturated polyester resin reinforced with varying weight fractions of particulate snail shell. 1(4), 39-44.
- Mandalari, G., Tomaino, A., Arcoraci, T., Martorana, M., Turco, V. L., Cacciola, F., Rich, G., Bisignano, C., Saija, A., Dugo, P. J. J. O. F. C., & Analysis. (2010). Characterization of polyphenols, lipids and dietary fibre from almond skins (*Amygdalus communis* L.). 23(2), 166-174.
- Mande, S. J. B. T. F. W. W. T., & technologies. (2005). Biomass gasifier-based power plants: potential, problems, and research needs for. 1.
- Mantia, F. L., Morreale, M., & Ishak, Z. M. J. J. O. A. P. S. (2005). Processing and mechanical properties of organic filler–polypropylene composites. 96(5), 1906-1913.
- Mazaya, G., Karseno, K., Yanto, T. J. T. J. O. A.-F. S., & Technology. (2020). Antimicrobial and phytochemical activity of coconut shell extracts. 8(5), 1090-1097.
- Mina, J. H., Valadez, A., Herrera-Franco, P. J., & Toledano, T. J. I. Y. C. (2009). Influencia del tiempo de almacenamiento en las propiedades estructurales de un almidón termoplástico de yuca (TPS). 11(2).
- Mirindi, D., Onchiri, R. O., & Thuo, J. J. A. S. (2021). Physico-mechanical properties of particleboards produced from macadamia nut shell and gum arabic. 11(23), 11138.
- Mosesson, J. G. J. C., & Recycling. (1979). The processing and use of waste straw as a constructional material. 3(3-4), 389-412.
- Mouritz, A. J. I. T. A. M., 1st ed., & Woodhead Publishing Ltd.: Cambridge, U. (2012). Fibre–polymer composites for aerospace structures and engines. 338-393.
- Mu, B., Wang, H., Hao, X., & Wang, Q. J. P. (2018). Morphology, mechanical properties and dimensional stability of biomass particles/high density polyethylene composites: Effect of species and composition. 10(3), 308.
- Muthoni, J., Nyamongo, D. J. J. O. H., & forestry. (2009). A review of constraints to ware Irish potatoes production in Kenya. 1(7), 98-102.
- Muzyczek, M. (2020). The use of flax and hemp for textile applications. In *Handbook of*

natural fibres (pp. 147-167). Elsevier.

- Nemli, G., Kırcı, H., Serdar, B., Ay, N. J. I. C., & Products. (2003). Suitability of kiwi (*Actinidia sinensis* Planch.) prunings for particleboard manufacturing. *17*(1), 39-46.
- Newton, J. A., & Morrell, J. J. J. F. P. J. (2020). Utilization of Ground Peanut Husk as an Alternative Fiber Material for Particleboard. *70*(4), 416-419.
- Njoku, R., Okon, A., & Ikpaki, T. J. N. J. O. T. (2011). Effects of variation of particle size and weight fraction on the tensile strength and modulus of periwinkle shell reinforced polyester composite. *30*(2), 87-93.
- Ntalos, G. A., Grigoriou, A. H. J. I. C., & Products. (2002). Characterization and utilisation of vine prunings as a wood substitute for particleboard production. *16*(1), 59-68.
- Ors, Y., & Kalaycioglu, H. J. T. J. A. F. (1991). Using of waste tea leaves on the particleboard industry. *15*, 968-974.
- Owodunni, A. A., Lamaming, J., Hashim, R., Taiwo, O. F. A., Hussin, M. H., Kassim, M. H. M., Bustami, Y., Sulaiman, O., Amini, M. H. M., & Hiziroglu, S. J. B. (2020). Properties of green particleboard manufactured from coconut fiber using a potato starch based adhesive. *15*(2), 2279-2292.
- Owodunni, A. A., Lamaming, J., Hashim, R., Taiwo, O. F. A., Hussin, M. H., Mohamad Kassim, M. H., Bustami, Y., Sulaiman, O., Amini, M. H. M., & Hiziroglu, S. J. P. C. (2020). Adhesive application on particleboard from natural fibers: A review. *41*(11), 4448-4460.
- Papadopoulos, A. N., Hague, J. R. J. I. C., & Products. (2003). The potential for using flax (*Linum usitatissimum* L.) shiv as a lignocellulosic raw material for particleboard. *17*(2), 143-147.
- Pelaez-Samaniego, M. R., Yadama, V., Garcia-Perez, T., Lowell, E., & Amidon, T. J. H. (2014). Effect of hot water extracted hardwood and softwood chips on particleboard properties. *68*(7), 807-815.
- Pirayesh, H., Khanjanzadeh, H., & Salari, A. J. C. P. B. E. (2013). Effect of using walnut/almond shells on the physical, mechanical properties and formaldehyde emission of particleboard. *45*(1), 858-863.
- Pirayesh, H., Khazaeian, A., & Tabarsa, T. J. C. P. B. E. (2012). The potential for using walnut (*Juglans regia* L.) shell as a raw material for wood-based particleboard manufacturing. *43*(8), 3276-3280.
- Prakash, R., Thenmozhi, R., Raman, S. N., Subramanian, C., & Divyah, N. J. S. C. (2021). An investigation of key mechanical and durability properties of coconut shell concrete with partial replacement of fly ash. *22*, E985-E996.
- Prasad, D. S., Krishna, A. R. J. I. J. O. O. S., & technology. (2011). Production and mechanical properties of A356. 2/RHA composites. *33*(51-58), 2019.

- Rachtanapun, P., Sattayarak, T., & Ketsamak, N. J. J. O. C. M. (2012). Correlation of density and properties of particleboard from coffee waste with urea–formaldehyde and polymeric methylene diphenyl diisocyanates. *46*(15), 1839-1850.
- Ramakrishnan, T., Gift, M., Chitradevi, S., Jegan, R., Jose, H., Subha, P., Nagaraja, H., Sharma, R., Selvakumar, P., Hailegiorgis, S. M. J. A. I. M. S., & Engineering. (2022). Study of Numerous Resins Used in Polymer Matrix Composite Materials. 2022.
- Reid, J., & Dryden, E. J. T. C. (1940). Anselme Payen-discoverer of cellulose. *62*, 43-45.
- Rowel, R., & Norimoto, M. J. M. G. (1988). Dimensional stability of bamboo particleboards made from acetylated particles. *34*(7), 627-629.
- Sadava, D. E., Hillis, D. M., & Heller, H. C. (2009). *Life: the science of biology* (Vol. 2). Macmillan.
- Saha, B. C. J. J. O. I. M., & biotechnology. (2003). Hemicellulose bioconversion. *30*(5), 279-291.
- Sahari, J., & Sapuan, S. J. R. A. M. S. (2011). Natural fibre reinforced biodegradable polymer composites. *30*(2), 166-174.
- Salasinska, K., & Ryszkowska, J. (2017). Physico-mechanical properties and dimensional stability of natural fibre composites fabricated from polyethylene waste and walnut shells. Conference paper ECCM-15th. In.
- Salleh, Z., Islam, M. M., & Ku, H. (2013). Tensile behaviours of activated carbon coconut shell filled epoxy composites. Proceedings of the 3rd Malaysian Postgraduate Conference (MPC 2013),
- Salmah, H., Marliza, M., Teh, P. J. I. J. O. E., & Technology. (2013). Treated coconut shell reinforced unsaturated polyester composites. *13*(02), 94-103.
- Santana-Méridas, O., González-Coloma, A., & Sánchez-Vioque, R. J. P. R. (2012). Agricultural residues as a source of bioactive natural products. *11*(4), 447-466.
- Santos, J., Dos Santos, I., De Souza, A., Prasad, S., & Dos Santos, A. J. J. O. F. S. (2002). Thermal stability and kinetic study on thermal decomposition of commercial edible oils by thermogravimetry. *67*(4), 1393-1398.
- Sareena, C., Ramesan, M., & Purushothaman, E. J. J. O. A. P. S. (2012). Utilization of peanut shell powder as a novel filler in natural rubber. *125*(3), 2322-2334.
- Sarı, B., Ayırmis, N., Nemli, G., Baharoğlu, M., Gümüşkaya, E., & Bardak, S. J. L. J. (2014). Effects of chemical composition of wood and resin type on properties of particleboard. *1*, 174-184.
- Sarsari, N. A., Pourmousa, S., & Tajdini, A. J. B. (2016). Physical and mechanical properties of walnut shell flour-filled thermoplastic starch composites. *11*(3), 6968-6983.

- Sepelev, I., & Galoburda, R. (2015). Industrial potato peel waste application in food production: a review.
- Shambharkar, R., Aditya, S., Kunal, R., & Dolly, W. J. I. R. J. E. T. (2018). Study on light weight characteristics of self compacting concrete using fine pumice powder and coconut shell. 5(3), 1379-1382.
- Shelke, A. S., Ninghot, K. R., Kunjekar, P. P., & Gaikwad, S. P. J. I. J. O. C. E. R. (2014). Coconut shell as partial replacement for coarse aggregate. 5(3), 211-214.
- Singh, A., Singh, S., Kumar, A. J. I. J. O. M. S., & Applications. (2013). Study of mechanical properties and absorption behaviour of coconut shell powder-epoxy composites. 2(5), 157-161.
- Somashekhar, T., Naik, P., Nayak, V., & Rahul, S. (2018). Study of mechanical properties of coconut shell powder and tamarind shell powder reinforced with epoxy composites. IOP Conference Series: Materials Science and Engineering,
- Sulaiman, N. S., Hashim, R., Amini, M. H. M., Sulaiman, O., & Hiziroglu, S. J. B. (2013). Evaluation of the properties of particleboard made using oil palm starch modified with epichlorohydrin. 8(1), 283-301.
- Surya, I., Olaiya, N., Rizal, S., Zein, I., Sri Aprilia, N., Hasan, M., Yahya, E. B., Sadasivuni, K. K., & Abdul Khalil, H. J. P. (2020). Plasticizer enhancement on the miscibility and thermomechanical properties of polylactic acid-chitin-starch composites. 12(1), 115.
- Tezara, C., Siregar, J. P., Lim, H., Fauzi, F., Yazdi, M. H., Moey, L., Lim, J. J. J. O. M. E., & Sciences. (2016). Factors that affect the mechanical properties of kenaf fiber reinforced polymer: A review. 10(2), 2159-2175.
- Thakur, V. K., & Thakur, M. K. J. C. p. (2014). Processing and characterization of natural cellulose fibers/thermoset polymer composites. 109, 102-117.
- The Welding Institue. (2024). *HOW ARE COMPOSITES MANUFACTURED?*,. <https://www.twi-global.com/technical-knowledge/faqs/faq-how-are-composites-manufactured>
- Thoemen, H., Irle, M., & Sernek, M. J. A. I. f. S. (2010). Wood-based panels.
- Ting, T. L., Jaya, R. P., Hassan, N. A., Yaacob, H., Jayanti, D. S., & Ariffin, M. A. M. J. J. T. (2016). A review of chemical and physical properties of coconut shell in asphalt mixture. 78(4).
- Turreda, L. J. U. T. J. (1983). Bagasse, wood and wood-bagasse particleboards bonded with urea formaldehyde and polyvinyl acetate/isocynate adhesives. 8(3), 66-78.
- Vasisth, R., & Chandramouli, P. (1975). *New panel boards from rice husks. FAO Background Paper.*
- Vasu, A., Reddy, C., Danaboyina, S., Manchala, G., & Chavali, M. J. J. P. S. A. (2017). The Improvement in mechanical properties of coconut shell powder as filter in HDPE

composites. *1*(2), 2-7.

Viswanathan, R., & Gothandapani, L. J. J. O. A. E. R. (1999). Optimum process variables for the production of coir pith particleboard. *74*(4), 331-337.

Vu, L. T., Cao, T. T. J. S., Agriculture, T. J. O., & Development, R. (2011). Study on technology of chipboard from rice husk and short fibers of coconut shell.

Wang, D., Sun, X. S. J. I. C., & products. (2002). Low density particleboard from wheat straw and corn pith. *15*(1), 43-50.

Wechsler, A., Zaharia, M., Crosky, A., Jones, H., Ramírez, M., Ballerini, A., Nuñez, M., Sahajwalla, V. J. M., & Design. (2013). Macadamia (*Macadamia integrifolia*) shell and castor (*Ricinus communis*) oil based sustainable particleboard: A comparison of its properties with conventional wood based particleboard. *50*, 117-123.

Wong, K. J. (2013). *Moisture absorption characteristics and effects on mechanical behaviour of carbon/epoxy composite: Application to bonded patch repairs of composite structures* Dijon].

Yulianto, M., Hartulistiyo, E., Nelwan, L. O., Agustina, S. E., & Gupta, C. J. I. J. O. R. E. D. (2023). Thermal Characteristics of Coconut Shells as Boiler Fuel. *12*(2).

Zajdenweg, C., Branco, G. F., Alamed, J., Decker, E. A., Castro, I. A. J. E. F. R., & Technology. (2011). Correlation between sensory and chemical markers in the evaluation of Brazil nut oxidative shelf-life. *233*(1), 109-116.

Zakaria, S. M., Idris, A., & Alias, Y. J. B. (2017). Lignin extraction from coconut shell using aprotic ionic liquids. *12*(3), 5749-5774.

Zhang, Y., Lu, X., Pizzi, A., Delmotte, L. J. E. J. O. W., & Products, W. (2003). Wheat straw particleboard bonding improvements by enzyme pretreatment. *61*(1), 49-54.

Zhao, S., Zhu, L., Gao, L., & Li, D. (2018). Limitations for microplastic quantification in the ocean and recommendations for improvement and standardization. In *Microplastic contamination in aquatic environments* (pp. 27-49). Elsevier.

Zheng, D., Zhang, Y., Guo, Y., & Yue, J. J. P. (2019). Isolation and characterization of nanocellulose with a novel shape from walnut (*Juglans regia* L.) shell agricultural waste. *11*(7), 1130.

7 Appendix

Table 7-1 CSP particle size distribution

R	SPS,mm	1	2	3	4	5	6	SUM
	Wt., g							
1	1000	364.44	324.44	257.78	41.19	9.94	1.78	999.57
2	1000	327.27	318.18	286.36	45.91	12.58	6.07	996.38
3	1000	311.28	326.85	291.83	48.73	12.04	4.65	995.39
4	1000	346.00	336.50	264.59	42.84	7.31	1.99	999.23
5	1000	300.97	300.00	305.83	64.18	19.57	9.08	999.63
6	1000	380.95	317.46	245.78	41.72	8.94	2.89	997.75
7	1000	320.65	329.35	277.17	52.66	13.97	5.77	999.58
8	1000	309.86	314.55	286.38	58.44	16.87	7.57	993.68
9	1000	339.80	311.22	269.39	58.11	15.44	5.45	999.41
10	1000	342.86	308.57	278.86	51.47	12.23	5.77	999.76
AV	1000	334.41	318.71	276.40	50.53	12.89	5.10	998.04
MF	1.00	0.34	0.32	0.28	0.05	0.01	0.01	1.00

Where: 1= 1+<1 mm, 2= 2 mm, 3=3.15 mm, 4=4mm, 5=5mm, 6= > 5 mm. The majority of the biomass laid in the range of 1 mm to 4 mm thus those sizes were utilized in this study.

Table 7-2 Acid Insoluble Lignin (AIL) of raw CSP

R	W	A	K L%
1	1	0.22	22.00
2	1	0.24	24.00
3	1	0.34	34.00
5	1	0.27	27.00
6	1	0.32	32.00
7	1	0.31	31.00
8	1	0.20	20.00
9	1	0.35	35.00
10	1	0.28	28.00
AV	1	0.28	28.30
SD		0.05	4.67

Where: W = Oven-dried weight of test specimen, g; A = Weight of Klason lignin, g

KL %= Klason lignin % = $100 (A/W) = 28.30 \pm 4.67$

Table 7-3 Acid soluble Lignin (ASL) of raw CSP

R	A	D	B	V, ml	W, g	ASL
1	0.46	10	0.04	575	1	2.39
2	0.48	10	0.04	575	1	2.52
3	0.54	10	0.05	575	1	2.81
4	0.47	10	0.04	575	1	2.45
5	0.47	10	0.04	575	1	2.44
6	0.49	10	0.04	575	1	2.55
7	0.45	10	0.04	575	1	2.35
8	0.48	10	0.04	575	1	2.51
9	0.48	10	0.04	575	1	2.50
10	0.53	10	0.05	575	1	2.77
AV		10	0.04	575	1	2.53
SD		0.00	0.00	0.00	0.00	0.14

Where: A= Absorbance (Peak), Lignin (g/l) = $B = (A/a) * D$, in dilute filtrate & $a = 110$

(constant). $D = V_d/V_o$, V_d =Vol of diluted filtrate, V_o =Vol of original filtrate taken = $50/5 = 10$

V = total volume of the filtrate, that is, 575 ml for wood. W = oven-dry weight of wood or pulp sample, g. ASL=Acid Soluble Lignin, % = $(B * V * 100) / (1000 * W) = 2.53 \pm 0.1$

Table 7-4 Hot-water extracts solubility

R	A	B	HWE %
1	10	9.29	7.10
2	10	9.31	6.90
3	10	9.20	8.00
4	10	9.25	7.50
5	10	9.44	5.60
6	10	9.23	7.70
7	10	9.27	7.30
8	10	9.52	4.80
9	10	9.56	4.40
10	10	9.41	5.90
AV		9.35	6.52
SD		0.13	1.26

Where: A and B = Oven-dried weight of test specimen before and after extraction

respectively, g. HWE%=Hot water extract content = 6.52 ± 1.2

Table 7-5 Holocellulose content of raw CSP

R	A	B	C %
1	2	1.19	59.50
2	2	1.11	55.50
3	2	1.10	55.00
4	2	1.11	55.50
5	2	1.23	61.50
6	2	1.08	54.00
7	2	1.15	57.50
8	2	1.05	52.50
9	2	1.01	50.50
10	2	1.20	60.00
AV		1.12	56.15
SD		0.07	3.47

Where: A = Oven-dried extract-free specimen weight, g. B= the constant weight of specimen

after air dried and put in a desiccator

$$C = \text{Holocellulose \% in the sample} = \frac{B}{A} * 100 = 56.15 \pm 3.47$$

Table 7-6 Holocellulose compositions of raw coconut shell

R	Hol,g	Hol %	Cellu,g	Hemi,g	Cellu %	Hemi%	Cellu % in SP	Hemi % in SP
1	2	56.15	0.81	1.19	40.55	59.45	22.77	33.38
2	2	56.15	0.86	1.14	43.20	56.80	24.26	31.89
3	2	56.15	0.80	1.20	39.85	60.15	22.38	33.77
4	2	56.15	0.82	1.18	41.15	58.85	23.11	33.04
5	2	56.15	0.81	1.19	40.40	59.60	22.68	33.47
6	2	56.15	0.84	1.16	42.20	57.80	23.70	32.45
7	2	56.15	0.87	1.13	43.50	56.50	24.43	31.72
8	2	56.15	0.88	1.12	44.00	56.00	24.71	31.44
9	2	56.15	0.85	1.15	42.50	57.50	23.86	32.29
10	2	56.15	0.87	1.13	43.30	56.70	24.31	31.84
AV	2	56.15	0.84	1.16	42.07	57.94	23.62	32.53
SD			0.03	0.03	1.26	1.26	0.71	0.71

Where: Hol = Holocellulose weight, g. Holo % =percentage of holocellulose in the test

specimen, Cellu = Cellulose weight in the holocellulose test specimen

Hemi =Hemicellulose weight in the holocellulose, g. = (holocellulose – cellulose)

Cellu % = Cellulose percentage in the holocellulose test specimen

Hemi % =Hemicellulose percentage in the holocellulose test specimen

Cellu % in SP = Cellulose percentage in the test specimen of coconut shell

Hemi % in SP =Hemicellulose percentage in the test specimen of coconut shell

Cellulose % in raw CSP= 23.62±0.71; Hemicellulose % in raw CSP= 32.53±0.7

Table 7-7 Acid Insoluble Lignin (AIL) of residue

R	W	A	K L %
1	1	0.34	34.00
2	1	0.36	36.00
3	1	0.31	31.00
4	1	0.29	29.00
5	1	0.33	33.00
6	1	0.30	30.00
7	1	0.38	38.00
8	1	0.28	28.00
9	1	0.29	29.00
10	1	0.27	27.00
AV	1	0.32	31.50
SD		0.03	2.64

Where:

W = Oven-dried weight of test specimen, g; A = Weight of Klason lignin, g

KL %= Klason lignin % = 100 (A/W) = 31.50±2.64

Table 7-8 Acid Soluble Lignin of CSP residue

R	A	D	B	V, ml	W, g	ASL
1	0.58	10	0.053	575	1	3.03
2	0.56	10	0.051	575	1	2.92
3	0.56	10	0.051	575	1	2.91
4	0.58	10	0.052	575	1	3.01
5	0.55	10	0.050	575	1	2.88
6	0.55	10	0.050	575	1	2.87
7	0.55	10	0.050	575	1	2.85
8	0.55	10	0.050	575	1	2.88
9	0.55	10	0.050	575	1	2.86
10	0.54	10	0.049	575	1	2.84
AV		10	0.051	575	1	2.90
SD		0	0.001	0	0	0.06

Where:

A= Absorbance (Peak); Lignin (g/l) =B= (A/a) *D, in dilute filtrate & a= 110 (constant)

D= Vd/Vo, Vd=Vol of diluted filtrate, Vo=Vol of original filtrate taken =50/5= 10

V = total volume of the filtrate, that is, 575 ml for wood

W = oven-dry weight of wood or pulp sample, g

ASL=Acid Soluble Lignin, % = $(B \cdot V \cdot 100) / (1000 \cdot W) = 2.90 \pm 0.06$

Table 7-9 Holocellulose content of CSP residue

R	A	B	C %
1	2	1.33	66.50
2	2	1.37	68.50
3	2	1.29	64.50
4	2	1.27	63.50
5	2	1.32	66.00
6	2	1.30	65.00
7	2	1.26	63.00
8	2	1.24	62.00
9	2	1.31	65.50
10	2	1.35	67.50
AV		1.30	65.20
SD		0.04	2.03

Where A = Oven-dried extract-free specimen weight, g. B= the constant weight of specimen

after air dried and put in a desiccator, C= Holocellulose % in the sample = $B/AX100=$

65.20 ± 2.03

Table 7-10 Holocellulose compositions of CSP residue

R	Hol,g	Hol %	Cellu,g	Hemi,g	Cellu %	Hemi%	Cellu % in SP	Hemi % in SP
1	2	65.20	1.15	0.85	57.50	42.50	37.49	27.71
2	2	65.20	1.19	0.81	59.50	40.50	38.79	26.41
3	2	65.20	0.95	1.05	47.50	52.50	30.97	34.23
4	2	65.20	1.00	1.00	50.00	50.00	32.60	32.60
5	2	65.20	1.12	0.88	56.00	44.00	36.51	28.69
6	2	65.20	1.07	0.93	53.50	46.50	34.88	30.32
7	2	65.20	1.14	0.86	57.00	43.00	37.16	28.04
8	2	65.20	1.03	0.97	51.50	48.50	33.58	31.62
9	2	65.20	0.92	1.08	46.00	54.00	29.99	35.21
10	2	65.20	1.06	0.94	53.00	47.00	34.56	30.64
AV	2	65.20	1.06	0.94	53.15	46.85	34.65	30.55
SD			0.09	0.09	4.45	4.45	2.90	2.90

Where:

Hol = Holocellulose weight, g. Holo % =percentage of holocellulose in the test specimen

Cellu = Cellulose weight in the holocellulose test specimen

Hemi =Hemicellulose weight in the holocellulose, g. = (holocellulose - cellulose)

Cellu % = Cellulose percentage in the holocellulose test specimen

Hemi % =Hemicellulose percentage in the holocellulose test specimen

Cellu % in SP = Cellulose percentage in the test specimen of coconut shell

Hemi % in SP =Hemicellulose percentage in the test specimen of coconut shell

Cellulose % in CSP residue = 34.65 ± 2.90 ; Hemicellulose % in CSP residue= 30.55 ± 2.90

Table 7-11 Moisture content of raw CSP

R	A (g)	B(g)	MC, %
1	10.03	9.48	5.48
2	10.04	9.51	5.28
3	10.00	9.34	6.60
4	10.01	9.51	5.00
5	10.00	9.31	6.90
6	10.00	9.38	6.20
7	10.11	9.42	6.82
8	10.23	9.66	5.57
9	10.30	9.77	5.15
10	10.00	9.40	6.00
AV	10.07	9.48	5.90
SD			0.61

Where: A=Initial Weight, B=Dry Weight, MC, % = moisture content % = $(A-B)/A * 100$

Table 7-12 Moisture content of CSP residue

R	A (g)	B(g)	MC, %
1	10.00	8.79	12.10
2	10.01	8.94	10.69
3	10.00	8.81	11.90
4	10.01	8.78	12.29
5	10.00	8.86	11.40
6	10.00	8.99	10.10
7	10.11	8.71	13.85
8	10.22	8.88	13.11
9	10.42	8.99	13.72
10	10.00	8.83	11.70
AV	10.08	8.86	12.09
SD			1.16

Where: A=Initial Weight, B=Dry Weight; MC, % = moisture content % = $(A-B)/A * 100$

Table 7-13 Ash content of CSP residue

R	B	DC	DC+B	DC+A	A	Ash, %
1	2	43.40	45.40	43.42	0.02	0.95
2	2	42.26	44.26	42.28	0.02	0.75
3	2	41.35	43.35	41.37	0.02	1.05
4	2	43.40	45.40	43.41	0.01	0.55
5	2	42.26	44.26	42.28	0.02	0.85
6	2	41.35	43.35	41.37	0.01	0.65
7	2	43.40	45.40	43.42	0.02	0.90
8	2	42.26	44.26	42.28	0.02	0.80
9	2	41.35	43.35	41.36	0.01	0.60
10	2	43.40	45.40	43.41	0.01	0.50
AV	2	42.44	44.44	42.46	0.02	0.76
SD	0	0.90	0.90	0.90	0.00	0.18

Where: B = Oven dry test specimen, g DC= Oven dry crucible, g

A= Ash weight, g

Ash, % = $A \times 100 / B = 0.76 \pm 0.18 \%$

Table 7-14 Ash content of raw CSP

Run	B	DC	DC+B	DC+A	A	Ash, %
1	2	43.40	45.40	43.42	0.02	0.90
2	2	42.26	44.26	42.28	0.02	0.85
3	2	41.35	43.35	41.36	0.01	0.60
4	2	43.40	45.40	43.42	0.02	0.95
5	2	42.26	44.26	42.28	0.02	1.00
6	2	41.35	43.35	41.37	0.02	0.80
7	2	43.40	45.40	43.42	0.02	1.15
8	2	42.26	44.26	42.28	0.02	0.85
9	2	41.35	43.35	41.37	0.02	1.00
10	2	43.40	45.40	43.41	0.01	0.50
AV	2	42.44	44.44	42.46	0.02	0.86
SD	0	0.90	0.90	0.90	0.00	0.19

Where:

B = Oven dry test specimen weight, g

DC= Oven dry crucible weight, g

A= Ash weight, g Ash, % = $A \times 100 / B = 0.86 \pm 0.19 \%$

Table 7-15 Tensile strength Parallel to the surface (TSP) of CSP particleboard

	<i>mm</i>	<i>Wt.%</i>	<i>Mm</i>	<i>N</i>	<i>mm</i>		<i>Mm</i>	<i>N</i>	<i>mm</i>		<i>mm</i>	<i>N</i>	<i>mm</i>	<i>MPa</i>	<i>MPa</i>	
<i>R</i>	<i>SPS</i>	<i>SW</i>	<i>t1</i>	<i>Fmax1</i>	<i>B</i>	<i>Rt1</i>	<i>t2</i>	<i>Fmax2</i>	<i>B</i>	<i>Rt2</i>	<i>t3</i>	<i>Fmax3</i>	<i>b</i>	<i>Rt3</i>	<i>RtAV</i>	
<i>1</i>	<i>2</i>	<i>30</i>	<i>8.21</i>	<i>611.28</i>	<i>50</i>	<i>1.49</i>	<i>7.00</i>	<i>511.35</i>	<i>50</i>	<i>1.46</i>	<i>6.13</i>	<i>164.36</i>	<i>50</i>	<i>0.54</i>	<i>1.16</i>	
<i>2</i>	<i>1</i>	<i>50</i>	<i>7.09</i>	<i>1198.51</i>	<i>50</i>	<i>3.38</i>	<i>6.28</i>	<i>469.33</i>	<i>50</i>	<i>1.50</i>	<i>7.53</i>	<i>1180.96</i>	<i>50</i>	<i>3.14</i>	<i>2.67</i>	
<i>3</i>	<i>1</i>	<i>50</i>	<i>7.57</i>	<i>604.19</i>	<i>50</i>	<i>1.60</i>	<i>7.33</i>	<i>7765.11</i>	<i>50</i>	<i>21.18</i>	<i>8.10</i>	<i>705.40</i>	<i>50</i>	<i>1.74</i>	<i>8.17</i>	
<i>4</i>	<i>1</i>	<i>30</i>	<i>6.80</i>	<i>1439.21</i>	<i>50</i>	<i>4.23</i>	<i>6.77</i>	<i>1512.50</i>	<i>50</i>	<i>4.47</i>	<i>6.59</i>	<i>1025.11</i>	<i>50</i>	<i>3.11</i>	<i>3.94</i>	
<i>5</i>	<i>4</i>	<i>10</i>	<i>5.27</i>	<i>668.77</i>	<i>50</i>	<i>2.54</i>	<i>6.24</i>	<i>501.09</i>	<i>50</i>	<i>1.61</i>	<i>8.15</i>	<i>585.09</i>	<i>50</i>	<i>1.44</i>	<i>1.86</i>	
<i>6</i>	<i>2</i>	<i>20</i>	<i>6.53</i>	<i>494.87</i>	<i>50</i>	<i>1.51</i>	<i>6.78</i>	<i>379.72</i>	<i>50</i>	<i>1.12</i>	<i>6.11</i>	<i>766.53</i>	<i>50</i>	<i>2.51</i>	<i>1.71</i>	
<i>7</i>	<i>1</i>	<i>20</i>	<i>6.51</i>	<i>1496.96</i>	<i>50</i>	<i>4.60</i>	<i>6.67</i>	<i>1002.35</i>	<i>50</i>	<i>3.01</i>	<i>5.66</i>	<i>1383.31</i>	<i>50</i>	<i>4.89</i>	<i>4.16</i>	
<i>8</i>	<i>3.15</i>	<i>50</i>	<i>7.67</i>	<i>503.34</i>	<i>50</i>	<i>1.31</i>	<i>6.94</i>	<i>78.39</i>	<i>50</i>	<i>0.23</i>	<i>9.00</i>	<i>836.71</i>	<i>50</i>	<i>1.86</i>	<i>1.13</i>	
<i>9</i>	<i>2</i>	<i>10</i>	<i>5.65</i>	<i>996.30</i>	<i>50</i>	<i>3.53</i>	<i>6.70</i>	<i>631.07</i>	<i>50</i>	<i>1.89</i>	<i>6.74</i>	<i>952.72</i>	<i>50</i>	<i>2.83</i>	<i>2.75</i>	
<i>10</i>	<i>3.15</i>	<i>40</i>	<i>5.85</i>	<i>387.50</i>	<i>50</i>	<i>1.33</i>	<i>7.29</i>	<i>535.41</i>	<i>50</i>	<i>1.47</i>	<i>6.79</i>	<i>170.67</i>	<i>50</i>	<i>0.50</i>	<i>1.10</i>	
<i>11</i>	<i>2</i>	<i>30</i>	<i>7.80</i>	<i>706.41</i>	<i>50</i>	<i>1.81</i>	<i>6.57</i>	<i>854.34</i>	<i>50</i>	<i>2.60</i>	<i>7.69</i>	<i>828.85</i>	<i>50</i>	<i>2.16</i>	<i>2.19</i>	
<i>12</i>	<i>2</i>	<i>10</i>	<i>4.85</i>	<i>613.62</i>	<i>50</i>	<i>2.53</i>	<i>5.44</i>	<i>550.78</i>	<i>50</i>	<i>2.02</i>	<i>5.77</i>	<i>878.97</i>	<i>50</i>	<i>3.05</i>	<i>2.53</i>	
<i>13</i>	<i>1</i>	<i>20</i>	<i>6.85</i>	<i>1234.63</i>	<i>50</i>	<i>3.61</i>	<i>6.16</i>	<i>773.70</i>	<i>50</i>	<i>2.51</i>	<i>5.30</i>	<i>879.44</i>	<i>50</i>	<i>3.32</i>	<i>3.15</i>	
<i>14</i>	<i>4</i>	<i>20</i>	<i>5.62</i>	<i>733.74</i>	<i>50</i>	<i>2.61</i>	<i>7.92</i>	<i>916.69</i>	<i>50</i>	<i>2.31</i>	<i>5.15</i>	<i>67.51</i>	<i>50</i>	<i>0.26</i>	<i>1.73</i>	
<i>15</i>	<i>2</i>	<i>30</i>	<i>6.82</i>	<i>223.22</i>	<i>50</i>	<i>0.65</i>	<i>6.60</i>	<i>988.43</i>	<i>50</i>	<i>3.00</i>	<i>6.30</i>	<i>710.61</i>	<i>50</i>	<i>2.26</i>	<i>1.97</i>	
<i>16</i>	<i>4</i>	<i>40</i>	<i>9.96</i>	<i>758.45</i>	<i>50</i>	<i>1.52</i>	<i>6.90</i>	<i>489.98</i>	<i>50</i>	<i>1.42</i>	<i>7.01</i>	<i>267.41</i>	<i>50</i>	<i>0.76</i>	<i>1.24</i>	
		<i>RtA</i>	<i>MPa</i>													<i>2.59</i>
		<i>V</i>														

Where:

Fmax= Maximum Load (N)

b=width of the reduced cross-section of the specimen measured in dry condition, in. (mm),

t=thickness of the specimen measured in dry condition, in. (mm),

R_t = Maximum Tensile strength MPa = $F_{max} / (b \cdot T)$

R is the run order, SPS is the shell particle size in mm, and SW is the shell particle weight percentage

R_{tAV} = the average Tensile strength of three replicates

Notes: it was obvious that the maximum TSP achieved when the particle size is 1mm and the resin content 50% = 8.17 MPa

R_{tOAV} = the overall average Tensile strength of the board = 2.59 MPa

Table 7-16 MOR of CSP particleboard

[illegible]

Where:

F_{max} is the maximum load in Newton (N)

L_1 is the distance between the centres of the support, b is the width of the test piece in mm, and t is the thickness of the test piece in mm

f_m is the Bending strength (MOR) (in N/mm^2) of each test piece is given by $f_m = \frac{3F_{ma} \cdot L_1}{2bt^2}$

R is the run order, SPS is the shell particle size in mm, and SW is the shell particle weight percentage, SD is the standard deviation.

$f_{m_{AV}}$ = the average MOR of the three replicates

Notes: it was obvious that the maximum MOR achieved when the particle size is 1mm and the resin content 70% = $16.2 \pm 1.22 N/mm^2$

MOR_{OAV} = the overall average of MOR = $11.03 N/mm^2$

Table 7-17 Water absorption (WA) of CS particleboard

[illegible]

Where:

W_{t01} , W_{t02} , W_{t03} and W_{t0AV} are the samples weight in replicates before immersion and the average weight

W_{t21} , W_{t22} , W_{t23} and W_{t2AV} are the samples weight in replicates after immersion and the average weight

SD is the standard deviation, WA is the water absorption percentage

R is the run order, SPS is the shell particle size in mm, and SW is the shell particle weight percentage, SD is the standard deviation.

Notes: it was obvious that the maximum water absorption at SPS 1mm and resin content equal 80% = 56.98 ± 2.91 %

WA_{OAV} = the overall average water absorption= 35.03%

Table 7-18 Thickness swelling THS of CS particleboard

	<i>mm</i>	<i>Wt.%</i>	<i>Initial t₀ (mm)</i>			<i>t₁ after 2h immersion (mm)</i>					<i>Δ in t after 2h</i>				<i>2h THS = (Gt)= (t₂−t₁)/ t₁ *100</i>					
<i>R</i>	SPS	SW	t ₀₁	t ₀₂	t ₀₃	T _{AV}	t ₁₁	t ₁₂	t ₁₃	Tl _{AV}	Δt ₁	Δt ₂	Δt ₃	ΔT _{AV}	THS ₁	THS ₂	THS ₃	THS _{AV}	SD	
<i>1</i>	2	30	7.94	7.27	5.72	6.97	8.62	8.44	7.19	8.08	0.68	1.17	1.47	1.11	8.62	16.13	25.79	16.85	7.03	
<i>2</i>	1	50	6.90	6.29	6.54	6.58	8.17	7.06	7.52	7.58	1.27	0.77	0.98	1.01	18.40	12.24	14.93	15.19	2.52	
<i>3</i>	1	50	7.37	5.57	7.08	6.67	9.52	7.12	7.35	8.00	2.16	1.55	0.27	1.32	29.26	27.80	3.81	20.29	11.67	
<i>4</i>	1	30	5.27	6.10	5.27	5.54	10.20	7.31	6.37	7.96	4.93	1.21	1.10	2.41	93.49	19.83	20.87	44.73	34.48	
<i>5</i>	4	10	5.87	5.31	7.03	6.07	7.03	6.41	7.29	6.91	1.16	1.10	0.26	0.84	19.73	20.80	3.74	14.76	7.80	
<i>6</i>	2	20	5.20	5.06	5.32	5.19	6.47	6.06	7.22	6.58	1.27	1.00	1.90	1.39	24.33	19.82	35.74	26.63	6.70	
<i>7</i>	1	20	5.27	6.69	5.24	5.73	6.55	7.93	6.51	7.00	1.29	1.24	1.27	1.26	24.40	18.52	24.26	22.39	2.74	
<i>8</i>	3.15	50	7.11	7.49	9.85	8.15	9.20	9.35	11.11	9.89	2.09	1.86	1.26	1.74	29.41	24.89	12.79	22.36	7.02	
<i>9</i>	2	10	4.70	5.57	6.31	5.53	5.91	6.85	7.01	6.59	1.21	1.28	0.71	1.07	25.74	23.06	11.21	20.00	6.31	
<i>10</i>	3.15	40	8.09	6.25	9.25	7.86	8.60	7.83	11.10	9.18	0.50	1.59	1.85	1.31	6.23	25.38	20.01	17.21	8.07	
<i>11</i>	2	30	6.50	5.96	6.44	6.30	8.56	6.65	7.67	7.63	2.06	0.68	1.24	1.33	31.64	11.47	19.18	20.76	8.31	
<i>12</i>	2	10	6.26	6.32	6.90	6.49	7.41	7.69	8.34	7.81	1.15	1.38	1.44	1.32	18.31	21.79	20.91	20.34	1.47	
<i>13</i>	1	20	6.88	5.60	5.93	6.14	9.26	10.87	7.58	9.23	2.38	5.27	1.64	3.10	34.56	94.11	27.68	52.11	29.83	
<i>14</i>	4	20	6.49	8.05	4.48	6.34	7.70	10.32	6.27	8.10	1.22	2.27	1.79	1.76	18.73	28.21	39.93	28.96	8.67	
<i>15</i>	2	30	5.83	5.12	5.26	5.40	7.21	6.25	7.40	6.95	1.38	1.13	2.13	1.55	23.63	22.03	40.55	28.74	8.38	
<i>16</i>	4	40	8.70	5.56	5.58	6.61	10.43	6.07	6.77	7.75	1.73	0.51	1.19	1.14	19.84	9.14	21.26	16.74	5.41	
	THS _{0AV}																		24.25	9.78

Where:

t_{01} , t_{02} , t_{03} and t_{0AV} are the samples thickness in replicates before immersion and the average weight

t_{11} , t_{12} , t_{13} and t_{2AV} are the samples thickness in replicates after immersion and the average weight

SD is the standard deviation, WA is the water absorption percentage

R is the run order, SPS is the shell particle size in mm, and SW is the shell particle weight percentage.

THS_{AV} = average thickness swelling, $TS = (Gt) = (t_2 - t_1) / t_1 * 100$, Δ in t after 2h = the difference in thickness after 2h

(Gt) = thickness swelling (TS) after 2h, t_1 = initial thickness and t_2 = final thickness

Notes: it was seen that the maximum thickness swelling at SPS 1mm and resin content equal 80% = 52.11 %

THS_{OAV} = the overall average thickness swelling = 24.25%

It was also observed that after 24h the samples disintegrated thus it wasn't possible to take their measurements

Table 7-19 Density of CS particleboard

1	mm	wt.%	Initial thickness (t0) (mm)					Wt0(g)					Density ρ(g/cm3)				
R	SPS	SW	t01	t02	t03	t0av	SD	Wt01	Wt02	Wt03	WtAv	SD	ρ_1	ρ_2	ρ_3	ρ_{av}	SD
1	2	30	7.94	7.27	5.72	6.97	0.93	27.84	24.36	19.53	23.91	3.41	0.14	0.13	0.14	0.14	0.00
2	1	50	6.90	6.29	6.54	6.58	0.25	20.59	19.27	19.18	19.68	0.64	0.12	0.12	0.12	0.12	0.00
3	1	50	7.37	5.57	7.08	6.67	0.79	22.24	16.81	23.83	20.96	3.01	0.12	0.12	0.13	0.13	0.01
4	1	30	5.27	6.10	5.27	5.54	0.39	22.51	20.15	19.22	20.62	1.39	0.17	0.13	0.15	0.15	0.02
5	4	10	5.87	5.31	7.03	6.07	0.71	19.52	18.06	20.84	19.47	1.14	0.13	0.14	0.12	0.13	0.01
6	2	20	5.20	5.06	5.32	5.19	0.11	18.20	15.83	18.98	17.67	1.34	0.14	0.13	0.14	0.14	0.01
7	1	20	5.27	6.69	5.24	5.73	0.68	17.81	22.85	17.51	19.39	2.45	0.14	0.14	0.13	0.14	0.00
8	3.15	50	7.11	7.49	9.85	8.15	1.21	22.08	23.57	27.19	24.28	2.15	0.12	0.13	0.11	0.12	0.01
9	2	10	4.70	5.57	6.31	5.53	0.66	17.73	18.28	20.87	18.96	1.37	0.15	0.13	0.13	0.14	0.01
10	3.15	40	8.09	6.25	9.25	7.86	1.24	18.15	21.40	23.59	21.05	2.23	0.09	0.14	0.10	0.11	0.02
11	2	30	6.50	5.96	6.44	6.30	0.24	22.72	17.40	22.31	20.81	2.42	0.14	0.12	0.14	0.13	0.01
12	2	10	6.26	6.32	6.90	6.49	0.29	18.95	20.82	23.37	21.05	1.81	0.12	0.13	0.14	0.13	0.01
13	1	20	6.88	5.60	5.93	6.14	0.54	22.63	16.21	21.44	20.09	2.79	0.13	0.12	0.14	0.13	0.01
14	4	20	6.49	8.05	4.48	6.34	1.46	21.25	23.36	15.66	20.09	3.25	0.13	0.12	0.14	0.13	0.01
15	2	30	5.83	5.12	5.26	5.40	0.31	19.21	17.42	16.47	17.70	1.14	0.13	0.14	0.13	0.13	0.00
16	4	40	8.70	5.56	5.58	6.61	1.48	21.81	17.81	17.94	19.19	1.85	0.10	0.13	0.13	0.12	0.01
																ρ_{oAV}	0.13

Where t_{01} , t_{02} , t_{03} and t_{0AV} are the samples initial thickness in replicates and the average weight

W_{t01} , W_{t02} , W_{t03} and W_{t0AV} are the samples initial weight in replicates and the average weight

SD is the standard deviation, ρ (g/cm^3) is the sample density = mass (m)/volume (Length * Width * Height)

R is the run order, SPS is the shell particle size in mm, and SW is the shell particle weight percentage.; ρ_{av} = density average,

Notes: it was seen that the maximum density at SPS 1mm and resin content equal 70% = $0.15 \text{ g}/\text{cm}^3$

ρ_{oAV} = the overall average density = $0.13 \text{ g}/\text{cm}^3$

Table 7-20 CSPB and MUFPB decomposition

PB	W0		W1		W2		W3		W4		WL (%) = (W0-W4/W0) *100	
NO	CS	CONT	CSPB	CONT	CS	CONT	CS	CONT	CS	CONT	CS WL (%)	CONT WL%
1	1.558	0.836	1.199	0.831	1.009	0.802	0	0.795	0	0.787	100	5.861
2	1.616	0.790	1.301	0.785	1.111	0.778	0	0.773	0	0.768	100	2.785
3	1.595	0.844	1.120	0.839	1.001	0.832	0	0.836	0	0.834	100	1.185
4	1.478	0.717	1.095	0.708	0.998	0.695	0	0.693	0	0.689	100	3.905
5	1.201	0.745	0.877	0.740	0.777	0.727	0	0.714	0	0.707	100	5.101
AV	1.490	0.786	1.118	0.781	0.979	0.767	0.000	0.762	0.000	0.757	100.000	3.767

Where:

CS =coconut shell, CONT = control panel

W_0 , W_1 , W_2 , W_3 and W_4 = are the initial Weight and weight of particleboard (PB) after week one, week two, week three and week respectively.

WL%= weight loss percentage