UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT AND CHARACTERIZATION OF ARROWROOT (Maranta arundinacea L.) FIBRE-REINFORCED THERMOPLASTIC STARCH BIOCOMPOSITES

TARIQUE JAMAL

DEVELOPMENT AND CHARACTERIZATION OF ARROWROOT (*Maranta arundinacea* L.) FIBRE-REINFORCED THERMOPLASTIC STARCH BIOCOMPOSITES

By

TARIQUE JAMAL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

July 2022

DEDICATION

To Al-Quran, the greatest source of knowledge

"Such as remember Allah, standing, sitting, and reclining, and consider the creation of the heavens and the earth, (and say): Our Lord! You created not this in vain. Glory be to You! Preserve us from the doom of Fire" (Surah Al-Imran 3: 191)

&

To my beloved father and mother

&

To my beloved grandfather and grandmother

&

To my awesome siblings

&

To my beloved wife

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT AND CHARACTERIZATION OF ARROWROOT (*Maranta arundinacea* L.) FIBRE-REINFORCED THERMOPLASTIC STARCH BIOCOMPOSITES

By

TARIQUE JAMAL

July 2022

Chairman : Mohd Sapuan bin Salit, PhD, Peng
Faculty : Engineering

Petroleum-based plastics are one of the most commonly used materials in the packaging industry, which has been a source of concern for the global environment. The increased production of harmful environmental plastic waste has fueled the development of natural-based, renewable, and biodegradable materials. Therefore, environmental sustainability and the absence of harmful carbon emissions during and after processing are desirable characteristics of potential materials. Furthermore, the widespread acceptance of natural fibres and biopolymers as green materials is being driven by the rapid depletion of petroleum resources, as well as a growing awareness of global environmental issues associated with the use of conventional plastics. Also, rising petrochemical prices and environmental concerns are driving the development of natural polymeric materials for a wide range of applications in food-packaging materials that are more consumer-friendly. Among these materials, arrowroot (*Maranta arundinacea* L.) has emerged as a vital and effective source of starch and fibres. Arrowroot belongs to the Marantaceae family, which is typically found in tropical forests. When compared to other agro-based products, arrowroot starch and fibres has some distinct advantages, including lower cost than other natural sources and greater accessibility. Therefore, several laboratory experiments were conducted to produce and characterize arrowroot fibres, biopolymers, and biocomposite films. The samples were developed using a solution casting method. Initially, arrowroot bagasse (ABF) and husk fibres (AHF) were extracted and the physical, chemical, thermal, morphological properties, as well as crystallinity, were characterized. The chemical composition analysis revealed that ABF has higher cellulose (45.97 %) than AHF (37.35 %), cassava bagasse (10.04 %), and corn hull (15.30 %). In addition, ABF is significantly low in lignin (2.78 %) and density (1.11 g/cm^3) than AHF, corn hull, and cassava. Concerning the above characterization of fibres, it was found that the lignocellulosic biomasses from arrowroot are alternative promising sustainable material, which can be used in food packaging as a renewable filler.

The second stage was designed to investigate the development of arrowroot starch (AS) films using glycerol (G) as a plasticizer at the ratio of 15, 30, and 45% (w/w, starch basis) to achieve a new biopolymer for the application of environmentally friendly materials. The developed films were analysed in terms of physical, structural, mechanical, thermal, environmental, and barrier properties. The incorporation of glycerol into AS film-making solution reduced the brittleness and fragility of films. An increment in glycerol concentration caused an increment in film thickness, moisture content, and solubility in water, whereas density and water absorption were reduced. The tensile strength and modulus of G-plasticized AS films were reduced significantly from 9.34 to 1.95 MPa and 620.79 to 36.08 MPa, respectively, while elongation at break was enhanced from 2.41 to 57.33 %. FTIR analysis revealed that intermolecular hydrogen bonding occurred between glycerol and AS in plasticized films compared to control films. The G-plasticized films showed higher thermal stability than control films. Water vapour permeability (WVP) of plasticized films increased by an increase in glycerol concentrations. Furthermore, a novel biodegradable thermoplastic arrowroot starch (TPAS) film containing arrowroot fibre (AF) at different concentrations (0, 2, 4, 6, 8, and 10 wt.%) was developed and characterized in terms of thermal, antibacterial activity, water vapor permeability (WVP), biodegradability, physical, morphological (FESEM), tensile and tear strength, and light transmittance properties. The TPAS/AF biocomposite film revealed a higher degradation temperature (313.02 °C) than other biocomposite films, indicating better thermal stability. Furthermore, increasing AF concentration led to a significant ($p < 0.05$) reduction in the linear burning rate and WVP of the biocomposite films from 248.9 to 115.2 mm/min and 8.18 $\times 10^{-10} \times$ g. s^{-1}.m^{-1}. Pa^{-1} to 5.20 $\times 10^{-10} \times$ g. s-1.m^{-1}. Pa^{-1}, respectively. The tensile and tear strengths of TPAS/AF composites were increased significantly from 2.42 to 15.22 MPa and 0.83 to 1.28 MPa, respectively, and the elongation was decreased from 46.62 to 6.21%. The findings revealed that after being reinforced with fibres, the mechanical properties enhanced, and the optimum filler content was 10%. Regardless of fibre loadings, the results of water absorption testing revealed that the composite films immersed in seawater and rainwater absorbed more water than distilled water. In addition, the incorporation of AF and control film showed an insignificant effect against three pathogenic bacteria including *Staphylococcus aureus* (ATCC 43300), *Escherichia coli* (ATCC 25922), and *Bacillus subtilis* (B29). The soil burial findings demonstrated that the weight loss of TPAS/AF biocomposite films was significantly higher than TPAS film. Overall, the reinforcement of arrowroot fibre with TPAS film improves the properties of biocomposites for environmentally friendly food packaging applications. The development of fully biodegradable packaging films is essential in the continuous effort to address current environmental issues and gradually replace commonly used conventional packaging materials.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PEMBANGUNAN DAN PENCIRIAN BIOKOMPOSIT KANJI TERMOPLASTIK DIPERKUAT GENTIAN UBI BEMBAN (*Maranta arundinacea* L.)

Oleh

TARIQUE JAMAL

Julai 2022

Pengerusi : Mohd Sapuan bin Salit, PhD, PEng
Fakulti : Kejuruteraan

Plastik berasaskan petroleum adalah salah satu bahan yang digunakan dalam industri pembungkusan, dan ia telah menjadi kebimbangan terhadap persekitaran global. Peningkatan pengeluaran sisa plastik yang amat berbahaya kepada alam sekitar telah memacu pembangunan bahan berasaskan semula jadi, yang boleh diperbaharui dan terbiodegradasi. Oleh itu, kemampanan alam sekitar dan ketiadaan pelepasan karbon berbahaya semasa dan selepas pemprosesan adalah ciri-ciri yang diingini bagi bahan berpotensi. Tambahan pula, penerimaan meluas terhadap gentian semula jadi dan biopolimer sebagai bahan hijau didorong oleh penyusutan pesat sumber petroleum, serta kesedaran yang semakin meningkat tentang isu alam sekitar global yang berkaitan dengan penggunaan plastik konvensional. Di antara bahan-bahan ini, ubi bemban atau lebih dikenali sebagai ubi bemban (*Maranta arundinacea* L.) telah muncul sebagai sumber kanji dan serat yang penting dan berkesan. Ubi bemban tergolong dalam keluarga *Marantaceae*, yang biasanya ditemui di hutan tropika. Sampel telah dibangunkan menggunakan kaedah tuangan larutan. Pada mulanya, gentian ampas ubi bemban (ABF) dan gentian sekam ubi bemban (AHF) diekstrak, seterusnya dicirikan dari segi sifat fizikal, kimia, haba, morfologi, serta kehabluran ABF dan AHF. Analisis komposisi kimia menunjukkan bahawa ABF mempunyai selulosa yang lebih tinggi (45.97%) daripada AHF (37.35%). Tambahan pula, kandungan lignin (2.78%) dan ketumpatan (1.11g/cm^3) ABF adalah ketara rendah berbanding dengan AHF, kulit jagung dan ubi kayu. Mengenai pencirian gentian di atas, didapati bahawa biojisim lignoselulosa daripada akar ubi bemban merupakan bahan mampan alternatif yang menjanjikan, yang boleh digunakan dalam pembungkusan makanan sebagai pengisi boleh diperbaharui.

Pada peringkat kedua pencirian filem kanji ubi bemban (AS) dijalankan menggunakan gliserol (G) sebagai pemplastik pada nisbah 15, 30, dan 45% (b/b, asas kanji). Filem yang dibangunkan telah dianalisis dari segi sifat fizikal, struktur, mekanikal, dan haba.. Penggabungan gliserol ke dalam pembuatan tuangan larutan filem AS mengurangkan kerapuhan, ketumpatan dan penyerapan air filem manakala ketebalan, kandungan lembapan dan keterlarutan dalam air meningkat. Kekuatan tegangan dan modulus filem AS yang diplastik-G telah berkurangan dengan ketara daripada 9.34 kepada 1.95 MPa dan 620.79 kepada 36.08 MPa, masing-masing, manakala pemanjangan semasa putus menigkat daripada 2.41 kepada 57.33%. Analisis FTIR mendedahkan bahawa ikatan hidrogen antara molekul berlaku antara gliserol dan AS dalam filem plastik berbanding filem kawalan. Tambahan pula, filem kanji ubi bemban (TPAS) termoplastik terbiodegradasi novel yang mengandungi serat ubi bemban (AF) pada kepekatan berbeza (0, 2, 4, 6, 8, dan 10 wt.%) telah dibangunkan dan dicirikan dari segi haba, aktiviti antibakteria, kebolehtelapan wap air (WVP), kebolehbiodegradan, fizikal, morfologi (FESEM), kekuatan tegangan dan koyak, dan sifat penghantaran cahaya. Filem biokomposit TPAS/AF mendedahkan suhu degradasi yang lebih tinggi (313.02 ℃) berbanding filem biokomposit yang lain, menunjukkan kestabilan terma yang lebih baik. Tambahan pula, peningkatan kepekatan AF membawa kepada pengurangan yang ketara ($p < 0.05$) dalam kadar pembakaran linear dan WVP bagi filem biokomposit daripada 248.9 kepada 115.2 mm/min dan $8.18 \times 10^{-10} \times g.\ s^{-1}.m^{-1}.\ Pa^{-1}$ hingga $5.20 \times 10^{-10} \times g.\ s^{-1}.m^{-1}.\ Pa^{-1}$, masing-masing. Kekuatan tegangan dan koyak komposit TPAS/AF telah meningkat dengan ketara daripada 2.42 kepada 15.22 MPa dan 0.83 kepada 1.28 MPa, dan pemanjangan telah menurun daripada 46.62 kepada 6.21%. Penemuan mendedahkan bahawa selepas diperkukuh dengan gentian, sifat mekanikal dipertingkatkan, dan kandungan pengisi optimum ialah 10%. Tanpa mengira beban gentian, keputusan ujian penyerapan air mendedahkan bahawa filem komposit yang direndam dalam air laut dan air hujan menyerap lebih banyak air daripada air suling. Di samping itu, penggabungan AF dan filem kawalan menunjukkan kesan yang tidak ketara terhadap tiga bakteria patogen termasuk *Staphylococcus aureus* (ATCC 43300), *Escherichia coli* (ATCC 25922), dan *Bacillus subtilis* (B29). Penemuan daripada ujian biodegradabiliti menunjukkan bahawa kehilangan berat filem biokomposit TPAS/AF adalah lebih tinggi daripada filem TPAS. Secara keseluruhannya, pengukuhan gentian ubi bemban dengan filem TPAS meningkatkan sifat biokomposit untuk aplikasi pembungkusan makanan mesra alam.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious, the Most Merciful

I am eternally grateful to Allah SWT for giving me the strength, courage, and knowledge to finish my thesis. This thesis could not have been completed without His blessing and guidance. My warmest appreciation goes to my outstanding supervisor, Professor Ir. Dr. Mohd. Sapuan Bin Salit, for his continuous encouragement and support during my research. Under his guidance, I became extremely driven to pursue a career in research and writing. After that, I would like to express my sincere gratitude to my co-supervisors, Professor Ts. Dr. Khalina binti Abdan (Department of Biological and Agricultural Engineering, UPM) and Associate Professor Dr. Edi Syams Zainudin (Department of Mechanical and Manufacturing Engineering, UPM), Dr. Ahmad Ilyas bin Rushdan (School of Chemical and Energy Engineering, UTM).

I would like to express my gratitude to Universiti Putra Malaysia for providing financial support through the Universiti Putra Malaysia Special Graduate Research Assistantship (SGRA) scholarship, Geran Putra Berimpak (GPB), UPM/800-3/3/1/GPB/2019/9679800, and Geran Putra Berimpak (GPB), UPM.RMC.800-3/3/1/GPB/2020/9694500.

My heartfelt thanks go to my mother and father (Nafees Ahmad) for their special prayers and moral support, which drove me to continue the program despite significant obstacles. A special thanks to my siblings, Saif, Akif, Amir, and Haseeb, for their continuous moral support. Besides that, thanks to my entire family, especially my grandfather and grandmother. Thank you also to my uncle (Anees Ahmad) for his moral support. I am also thankful to everyone who helped me to complete this research successfully, including Dr. Faisal, Dr. Zatil, and Dr. Gohar. Finally, I would like to thank all my religious seniors, especially Dr. Zafar Alam, Moulana Abdul Aziz, Er. Meer Rashid, Prof. Faraheem (AMU, Aligarh), and Imran Ahmed, for their encouragement and moral support throughout this project.

Jazakumullahu Khairan!

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

Mohd Sapuan bin Salit@ Sinon, PhD
Professor, Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Khalina binti Abdan, PhD
Professor, Ts.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Edi Syams bin Zainudin, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Ahmad Ilyas bin Rushdan, PhD
Senior Lecturer
Faculty of Chemical and Energy Engineering
Universiti Teknologi Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 13 October 2022

Declaration by graduate student

I hereby confirm that:

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

Signature: ________________________ Date: ________________

Name and Matrix No.: Tarique Jamal; ________

Declaration by Members of Supervisory Committee

This is to confirm that:

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

Signature: ________________________________
Name of Chairman of Supervisory Committee: Professor Ir. Dr. Mohd Sapuan bin Salit

Signature: ________________________________
Name of Member of Supervisory Committee: Professor Ts. Dr. Khalina binti Abdan

Signature: ________________________________
Name of Member of Supervisory Committee: Associate Professor Dr. Edi Syams bin Zainudin

Signature: ________________________________
Name of Member of Supervisory Committee: Dr. Ahmad Ilyas bin Rushdan

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

%	Percentage
μm	Micrometer
g	Gram
h	Hour
M_f	Weight final
M_i	Weight initial
mm	Milimeter
MPa	Mega pascal
^{o}	Degree
^oC	Degree celcius
T_g	Glass transition
T_{Onset}	Onset temperature
T_p	Peak temperature
T_r	Light transmittance
V	Volume
W_L	Weight loss
wt.%	Weight percentage
Δm	Weight difference
ρ	Density

LIST OF ABBREVIATIONS

ABF	Arrowroot bagasse fibre
ADF	Acid detergent fibre
AF	Arrowroot fibre
AHF	Arrowroot husk fibre
ANOVA	Analysis Of Variance
AS	Arrowroot starch
ASTM	American Society for Testing and Materials
DSC	Differential Scanning Calorimetry
DTG	Derivative thermogravimetry
FESEM	Field emission scanning electron microscopy
FTIR	Fourier Transform Infrared
G	Glycerol
NDF	Neutral detergent fibre
SEM	Scanning Electron Microscopy
TGA	Thermal-gravimetric analysis
TPAS	Thermoplastic arrowroot starch
TS	Tensile strength
UTM	Universal testing machine
WVP	Water vapor permeability
XRD	X-ray diffraction

CHAPTER 1

INTRODUCTION

1.1 Background

The abundance of petroleum-based waste disposal has significantly contributed to rising environmental pollution, causing problems for both natural life as well as human health. Plastic's invention escorted in a revolution in material production in a variety of industries, including medicine, automobiles, electronics, and packaging (Sharuddin et al., 2016). It is distinguished by its reliability, heat resistance, and appropriateness for large scale production. The global production of synthetic plastics reached 140 million tons annually, an increase of 2% per year (Siracusa, 2019). Between 1950 and 2017, an estimated 9,200 million metric tons of synthetic plastics were produced, with 5,300 metric tons entering landfills, dumps, or the environment (Gavigan et al., 2020). This demonstrates that most of the plastic rubbish that landed up in landfills in extremely high and takes up a significant amount of space. Because plastics are certainly valuable and useful in our daily lives, several material engineers and researchers are attempting to design plastic materials that are both safer and much better for the environment. Bioplastics, which are derived from plant crops instead of fossil fuels, are being developed by manufactures as a more environmentally friendly substitute for petroleum-based plastics. Some scientists are trying to find a way to make recycling more efficient, with the goal of optimizing the process of transforming plastics back into the fossil fuels that they came from. All these researchers understand that plastics are not ideal, but an essential and vital component of our present and future applications (Rhim et al., 2013). These issues have motivated researchers and scientists to design and develop environmentally friendly advanced materials produced from renewable resources to substitute non-biodegradable materials in a variety of applications, protecting the green environmental. Among these source materials, arrowroot biopolymers and biocomposites offer numerous benefits, including outstanding reliability, low cost, availability, biodegradability, as well as high content of starch.

Arrowroot (*Maranta arundinacea* L.) is a large perennial herb native to the tropical forest that belongs to the *Marantaceae* family. The arrowroot plant is primarily found in the West Indies (Jamaica), Brazil, Indonesia, Malaysia, Philippines, India, and Sri Lanka (Nogueira et al., 2018). Arrowroot starch has excellent properties such as digestibility and gelling ability, and the highest amylose content (40.86%) (Gordillo et al., 2014), competing with corn starch (28-33%), wheat starch (30-32%), potato (18-20%), and cassava starch (16-19%), all of which are required for film production. Previous research has shown that the amylose content of starch influences its film-forming properties; hydrogen bonding linear chains together forms strong and stiff films. As a result, the high amylose content of arrowroot starch produces stronger films than other starch sources. A significant amount of waste arrowroot fibres is obtained during the arrowroot starch extraction process. According to a literature, arrowroot rhizomes comprise 38.1% of bagasse fibre (Branco et al., 2019). Branco et al. (2019) found that the arrowroot bagasse fibres are coarser as well as longer in comparison to cassava bagasse fibres. Biopolymer films were made from arrowroot starch employing a solution casting process with 15 to 45% (by weight) glycerol as a plasticizer. The results revealed that incorporating 30 % glycerol into the biopolymer was the most effective glycerol concentration, resulted in outstanding thermal and physical properties. Despite having adequate characteristics, the developed biopolymer has certain drawbacks, significantly such as poor tensile and water resistance. Hence, to overwhelm such drawbacks, arrowroot starch reinforced by arrowroot fibre is expected to produce better outcomes. Meanwhile, researchers investigated the impact of blackberry pulp incorporation on the physical, mechanical, and barrier properties of composite films made from arrowroot starch and blackberry pulp (Nogueira, Soares, et al., 2019). Likewise, Fakhouri et al. (2019) investigated the effect of cranberry powder incorporation on the microstructure and thermal properties of arrowroot starch/cranberry powder composites. Recently, De Sá et al. (2015) examined the characterization of nano whiskers cellulose derived from arrowroot fibre.

Up to date, there has been insufficient research on the applications of arrowroot biopolymers, fibres, and biocomposite. There has been a significant amount of work published on arrowroot starch in terms of characterization and application. No research has been conducted on the physicochemical, thermal, and morphological properties of arrowroot fibres. As a result, the focus of this research is on isolating arrowroot fibres and starch from arrowroot plant parts such as tubers and developing arrowroot starch biopolymer composites with arrowroot starch as a matrix.

1.2 Problem statements

Factors such as increased environmental awareness, societal concerns, governmental policies, and the depletion of petrochemical resources have accelerated the rapid growth of new green materials such as eco-friendly packaging films. The proper disposal of petroleum-based plastics, once they have served their purpose, has become a major global environmental issue that must be addressed immediately. Landfilling and incineration are the two most widely used disposal methods. However, due to the significant trash disposal, landfill capacity is rapidly diminishing. Increased pollution from the use of plentiful plastics and pollutants from cremation contribute significantly to environmental health issues. As a result, government laws on using non-renewable and non-biodegradable products have become stricter over time, in order to preserve a clean environment for future generations.

In recent years, most polymers used in packaging are still petroleum-based. The widespread use of petroleum-based materials increases CO_2 emissions, which leads to global climate change. Hence, to reduce reliance on petroleum-based polymers, this research attempted to use a 100% renewable and biodegradable biopolymer derived from arrowroot rhizomes (*Maranta arundinacea* L.). The rhizome of the arrowroot plant is a good source of starch, bagasse fibre, and husk fibre. However, because such a bio-sourced is presently underutilized, very little research on its development as a green packaging material have been reported. As a result, in the current work, arrowroot starch and arrowroot fibres were used to generate completely biodegradable films and biocomposite films as an environmentally friendly food packaging material. However, because of its hydroxyl or polar groups, arrowroot starch, like most other biopolymers, is hydrophilic. The problems relating to brittleness, processability, high moisture sensitivity, quick retrogradation, poor mechanical and barrier properties, and poor mechanical and barrier characteristics are the major challenges for the development of starches as packaging films (Sanyang et al., 2016a). The limitations can be solved by reinforcing arrowroot starch with arrowroot fibres into high-performance thermoplastic starch for packaging applications. To the best of author's knowledge, no research has been conducted on the characterization of arrowroot fibres and their application in reinforcing biopolymer composite films.

1.3 Research objectives

The overall objective of this research is to develop and characterize environmentally friendly arrowroot (*Maranta arundinacea* L.) fibre reinforced arrowroot starch biocomposite films. The research objectives can be specified into:

1. To characterize the arrowroot fibres from arrowroot tubers (Bagasse, and Husk) to explore their potential to develop a new fully biodegradable and environmentally friendly composite film.

2. To evaluate the effect of glycerol concentration on the physical, mechanical, thermal, and barrier properties of arrowroot starch-based films.

3. To determine the physical, morphological, and mechanical properties of arrowroot fibre reinforced arrowroot starch biocomposites at different fibre loading.

4. To determine the thermal, biodegradability, water barrier, and antimicrobial properties of arrowroot fibre reinforced arrowroot starch biocomposites at different fibre loading.

1.4 Significance of the research

1. This research aims to contribute to this growing area of study by investigating the information in developing high-performance biodegradable bio-packaging films derived from arrowroot starch.

2. To address environmental problems, which arise from the nonbiodegradable disposal, such type of environmentally friendly packaging films (100% biodegradable polymer composites) which is made by a single source (arrowroot) for starch and fibre can be used (instead of the use of synthetic polymer and synthetic polymer composites).

3. This research also reduced the wastage issue by providing the platform for making use of agricultural products wastage into fibres and biopolymers.

4. The successful development of such green materials from arrowroot would provide good opportunities to improve the standard of living of the farmers who cultivated arrowroot by developing economically in rural areas.

5. This research may also include the effort to reveal the potential of arrowroot starch and fibre in developing green products; else, such plentiful resources may be underutilized.

1.5 Scope of research

This research focused on the extraction of biopolymers and natural fibres from arrowroot tubers, as well as the production of biocomposites. A series of experiments were conducted to characterize arrowroot starch and fibres, as well as biopolymers and biocomposite films. The films were developed using a solution casting method with the addition of glycerol. The biocomposite films were developed in three stages using arrowroot fibres and arrowroot starch. The first phase involved investigating the physicochemical, morphological, and thermal properties of arrowroot starch and fibres in order to determine the feasibility of using arrowroot starch and fibres to develop materials with good thermal and mechanical properties for packaging applications. The second phase involved investigating the effect of varying concentrations of glycerol plasticizer on the physical, thermal, morphological, biodegradability, and mechanical properties of starch-based films. In the final phase, the characterized arrowroot fibre was utilized as reinforcement for biopolymer films to improve the matrix properties. Thus, the effect of arrowroot fibre loading (0-10 wt.%) on the physical, thermal, mechanical, water barrier, and antimicrobial properties of biocomposite films was investigated.

1.6 Structure of the thesis

The thesis structure follows Universiti Putra Malaysia alternative thesis format based on publications. Each research chapter (4–7) signifies distinct research that has its own: ‘Introduction’, ‘Materials and methods’, ‘Results and discussion’, and ‘Conclusion’. Further details on the thesis structure are as presented below.

Chapter 1

This chapter clearly describes the problem statement and research objectives. This chapter also demonstrated the significance and contribution of the research, as well as the scope and limitations of the research.

Chapter 2

This chapter provides a comprehensive review of the literature in the key areas related to the title of this thesis. In addition, the chapter discusses the research gaps identified through the literature review.

Chapter 3

This methodology chapter contains every activity related to this research, from material preparation to material processing, testing methods, and data collection and analysis.

Chapter 4

This chapter presents the first article entitled "Extraction and Characterization of a Novel Natural Lignocellulosic (Bagasse and Husk) Fibres from Arrowroot (*Maranta arundinacea* L.)". In this article, the physical, morphological, structural, and thermal properties of arrowroot bagasse and husk fibres were investigated.

Chapter 5

This chapter presents the second article entitled "Effect of glycerol plasticizer loading on the physical, mechanical, thermal, and barrier properties of arrowroot (*Maranta arundinacea* L.) starch biopolymers". In this article, the effect of glycerol plasticizer at different concentrations (15, 30, and 45%) on the properties of the arrowroot starch-based film was investigated.

Chapter 6

This chapter presents the third article entitled "Physical, mechanical and morphological performances of arrowroot (*Maranta arundinacea* L.) fibre reinforced arrowroot starch biopolymer composites". The aim of this article was to develop and characterize biocomposite films based on arrowroot starch matrix and arrowroot fibre as reinforcement filler at different loadings.

Chapter 7

This chapter presents the fourth article entitled "Thermal, flammability, and antimicrobial properties of arrowroot (*Maranta arundinacea* L.) fibre reinforced arrowroot starch biopolymer composites for food packaging applications". This article studied the effect of various loading of arrowroot fibre (2%, 4%, 6%, 8%, and 10%) on the thermal, antimicrobial, biodegradability, flammability, and water barrier properties of thermoplastic arrowroot starch-based biocomposite films.

Chapter 8

This chapter presents general conclusions collected from different research articles, as well as relevant suggestions and recommendations for further research.

References

Abdal-Hay, A., Suardana, N. P. G., Choi, K.-S., & Lim, J. K. (2012). Effect of diameters and alkali treatment on the tensile properties of date palm fiber reinforced epoxy composites. *International Journal of Precision Engineering and Manufacturing*, *13*(7), 1199–1206.

Abral, H., Chairani, M. K., Rizki, M. D., Mahardika, M., Handayani, D., Sugiarti, E., Muslimin, A. N., Sapuan, S. M., & Ilyas, R. A. (2021). Characterization of compressed bacterial cellulose nanopaper film after exposure to dry and humid conditions. *Journal of Materials Research and Technology*, *11*, 896–904. https://doi.org/10.1016/j.jmrt.2021.01.057

Alotaibi, M. D., Alshammari, B. A., Saba, N., Alothman, O. Y., Sanjay, M. R., Almutairi, Z., & Jawaid, M. (2019). Characterization of natural fiber obtained from different parts of date palm tree (Phoenix dactylifera L.). *International Journal of Biological Macromolecules*, *135*, 69–76. https://doi.org/10.1016/j.ijbiomac.2019.05.102

Alsubari, S., Zuhri, M. Y. M., Sapuan, S. M., Ishak, M. R., Ilyas, R. A., & Asyraf, M. R. M. (2021). Potential of natural fiber reinforced polymer composites in sandwich structures: A review on its mechanical properties. *Polymers*, *13*(3), 1–20. https://doi.org/10.3390/polym13030423

Arthanarieswaran, V. P., Kumaravel, A., & Saravanakumar, S. S. (2015). Characterization of new natural cellulosic fiber from Acacia leucophloea bark. *International Journal of Polymer Analysis and Characterization*, *20*(4), 367–376.

Ashori, A., Nourbakhsh, A., & Tabrizi, A. K. (2014). Thermoplastic Hybrid Composites using Bagasse, Corn Stalk and E-glass Fibers: Fabrication and Characterization. *Polymer - Plastics Technology and Engineering*, *53*(1), 1–8. https://doi.org/10.1080/03602559.2013.832854

Ayu, R. S., Khalina, A., Harmaen, A. S., Zaman, K., Isma, T., Liu, Q., Ilyas, R. A., & Lee, C. H. (2020). Characterization Study of Empty Fruit Bunch (EFB) Fibers Reinforcement in Poly(Butylene) Succinate (PBS)/Starch/Glycerol Composite Sheet. *Polymers*, *12*(7), 1571. https://doi.org/10.3390/polym12071571

Belouadah, Z., Ati, A., & Rokbi, M. (2015). Characterization of new natural cellulosic fiber from Lygeum spartum L. *Carbohydrate Polymers*, *134*, 429–437.

Borba, P. M., Tedesco, A., & Lenz, D. M. (2014). Effect of reinforcement nanoparticles addition on mechanical properties of SBS/Curauá fiber composites. *Materials Research*, *17*(2), 412–419. https://doi.org/10.1590/S1516-14392013005000203

Brinchi, L., Cotana, F., Fortunati, E., & Kenny, J. M. (2013). Production of nanocrystalline cellulose from lignocellulosic biomass: Technology and applications. *Carbohydrate Polymers*, *94*(1), 154–169. https://doi.org/10.1016/j.carbpol.2013.01.033

Carvalho, K. C. C., Mulinari, D. R., Voorwald, H. J. C., & Cioffi, M. O. H. (2010).

Chemical modification effect on the mechanical properties of hips/coconut fiber composites. *BioResources*, *5*(2), 1143–1155.

Catto, A. L., Stefani, B. V., Ribeiro, V. F., & Santana, R. M. C. (2014). Influence of coupling agent in compatibility of post-consumer HDPE in thermoplastic composites reinforced with eucalyptus fiber. *Materials Research*, *17*, 203–209. https://doi.org/10.1590/S1516-14392014005000036

Chen, H. (2014). Biotechnology of Lignocellulose. In *Biotechnology of Lignocellulose: Theory and Practice*. Springer Netherlands. https://doi.org/10.1007/978-94-007-6898-7

Chianelli-Junior, R., Reis, J. M. L., Cardoso, J. L., & Castro, P. F. (2013). Mechanical characterization of sisal fiber-reinforced recycled HDPE composites. *Materials Research*, *16*(6), 1393–1397. https://doi.org/10.1590/S1516-14392013005000128

Da Costa Castro, C. D. P., Dias, C. G. B. T., & De Assis Fonseca Faria, J. (2010). Production and evaluation of recycled polymers from açaí fibers. *Materials Research*, *13*(2), 159–163. https://doi.org/10.1590/s1516-14392010000200007

De Carvalho Mendes, C. A., De Oliveira Adnet, F. A., Leite, M. C. A. M., Furtado, C. R. G., & De Sousa, A. M. F. (2015). Chemical, physical, mechanical, thermal and morphological characterization of corn husk residue. *Cellulose Chemistry and Technology*, *49*(9–10), 727–735.

De Rosa, I. M., Santulli, C., & Sarasini, F. (2010). Mechanical and thermal characterization of epoxy composites reinforced with random and quasi-unidirectional untreated Phormium tenax leaf fibers. *Materials and Design*, *31*(5), 2397–2405. https://doi.org/10.1016/j.matdes.2009.11.059

De Sá, R. M., De Miranda, C. S., & José, N. M. (2015). Preparation and characterization of nanowhiskers cellulose from fiber arrowroot (maranta arundinacea). *Materials Research*, *18*(Suppl 2), 225–229. https://doi.org/10.1590/1516-1439.366214

Deswina, P., & Priadi, D. (2020). Development of Arrowroot (Maranta arundinacea L.) as Functional Food Based of Local Resource. *IOP Conference Series: Earth and Environmental Science*, *439*(1), 012041. https://doi.org/10.1088/1755-1315/439/1/012041

Edhirej, A., Sapuan, S. M., Jawaid, M., & Zahari, N. I. (2015). Cassava: Its polymer, fiber, composite, and application. *Polymer Composites*, *38*(3), 555–570. https://doi.org/doi:10.1002/pc.23614

Edhirej, A., Sapuan, S. M., Jawaid, M., & Zahari, N. I. (2017). Preparation and characterization of cassava bagasse reinforced thermoplastic cassava starch. *Fibers and Polymers*, *18*(1), 162–171. https://doi.org/10.1007/s12221-017-6251-7

Erdman, M. D., & Erdman, B. A. (1984). Arrowroot (Maranta arundinacea), food, feed, fuel, and fiber resource. *Economic Botany*, *38*(3), 332–341. https://doi.org/10.1007/BF02859011

Fakhouri, F. M., Nogueira, G. F., de Oliveira, R. A., & Velasco, J. I. (2019). Bioactive edible films based on arrowroot starch incorporated with cranberry powder: Microstructure, thermal properties, ascorbic acid content and sensory analysis. *Polymers*, *11*(10). https://doi.org/10.3390/polym11101650

Fu, S. Y., Feng, X. Q., Lauke, B., & Mai, Y. W. (2008). Effects of particle size, particle/matrix interface adhesion and particle loading on mechanical properties of particulate-polymer composites. *Composites Part B: Engineering*, *39*(6), 933–961. https://doi.org/10.1016/j.compositesb.2008.01.002

Galindez, A., Daza, L. D., Homez-Jara, A., Eim, V. S., & Váquiro, H. A. (2019). Characterization of ulluco starch and its potential for use in edible films prepared at low drying temperature. *Carbohydrate Polymers*, *215*(March), 143–150. https://doi.org/10.1016/j.carbpol.2019.03.074

Gelfuso, M. V., Da Silva, P. V. G., & Thomazini, D. (2011). Polypropylene matrix composites reinforced with coconut fibers. *Materials Research*, *14*(3), 360–365. https://doi.org/10.1590/S1516-14392011005000056

Gelfuso, M. V., Thomazini, D., De Souza, J. C. S., & De Lima Junior, J. J. (2014). Vibrational analysis of coconut fiber-PP composites. *Materials Research*, *17*(2), 367–372. https://doi.org/10.1590/S1516-14392013005000200

Hazrati, K. Z., Sapuan, S. M., Zuhri, M. Y. M., & Jumaidin, R. (2021). Extraction and Characterization of Potential Biodegradable Materials Based on Dioscorea hispida Tubers. *Polymers*, *13*(4), 584. https://doi.org/10.3390/polym13040584

Hazrol, M. D., Sapuan, S. M., Zainudin, E. S., Zuhri, M. Y. M., & Abdul Wahab, N. I. (2021). Corn Starch (Zea mays) Biopolymer Plastic Reaction in Combination with Sorbitol and Glycerol. *Polymers*, *13*(2), 242. https://doi.org/10.3390/polym13020242

Husseien, M., Amer, A. A., El-Maghraby, A., & Hamedallah, N. (2009). A comprehensive characterization of corn stalk and study of carbonized corn stalk in dye and gas oil sorption. *Journal of Analytical and Applied Pyrolysis*, *86*(2), 360–363. https://doi.org/10.1016/j.jaap.2009.08.003

Ibrahim, M. I. J., Sapuan, S. M., Zainudin, E. S., & Zuhri, M. Y. M. (2019). Extraction, chemical composition, and characterization of potential lignocellulosic biomasses and polymers from corn plant parts. *BioResources*, *14*(3), 6485–6500. https://doi.org/10.15376/biores.14.3.6485-6500

Ilyas, R. A., Sapuan, S. M., Atikah, M. S. N., Asyraf, M. R. M., Rafiqah, S. A., Aisyah, H. A., Nurazzi, N. M., & Norrahim, M. N. F. (2021). Effect of hydrolysis time on the morphological, physical, chemical, and thermal behavior of sugar palm nanocrystalline cellulose (Arenga pinnata (Wurmb.) Merr). *Textile Research Journal*, *91*(1–2), 152–167. https://doi.org/10.1177/0040517520932393

Ilyas, R. A., Sapuan, S. M., Ibrahim, R., Abral, H., Ishak, M. R., Zainudin, E. S., Atikah, M. S. N., Mohd Nurazzi, N., Atiqah, A., Ansari, M. N. M., Syafri, E., Asrofi, M., Sari, N. H., & Jumaidin, R. (2019). Effect of sugar palm nanofibrillated cellulose concentrations on morphological, mechanical and physical properties of biodegradable films based on agro-waste sugar palm (Arenga pinnata (Wurmb.) Merr) starch. *Journal of Materials Research and Technology*, *8*(5), 4819–4830. https://doi.org/10.1016/j.jmrt.2019.08.028

Ilyas, R. A., Sapuan, S. M., & Ishak, M. R. (2018). Isolation and characterization of nanocrystalline cellulose from sugar palm fibres (Arenga Pinnata). *Carbohydrate Polymers*, *181*(June 2017), 1038–1051. https://doi.org/10.1016/j.carbpol.2017.11.045

Ilyas, R. A., Sapuan, S. M., Ishak, M. R., & Zainudin, E. S. (2017). Effect of delignification on the physical, thermal, chemical, and structural properties of sugar palm fibre. *BioResources*, *12*(4), 8734–8754.

Ilyas, R. A., Sapuan, S. M., Ishak, M. R., & Zainudin, E. S. (2018). Development and characterization of sugar palm nanocrystalline cellulose reinforced sugar palm starch bionanocomposites. *Carbohydrate Polymers*, *202*(May), 186–202. https://doi.org/10.1016/j.carbpol.2018.09.002

Indran, S., & Raj, R. E. (2015). Characterization of new natural cellulosic fiber from Cissus quadrangularis stem. *Carbohydrate Polymers*, *117*, 392–399.

Indran, S., Raj, R. E., & Sreenivasan, V. S. (2014). Characterization of new natural cellulosic fiber from Cissus quadrangularis root. *Carbohydrate Polymers*, *110*, 423–429.

Ishak, M. R., Sapuan, S. M., Leman, Z., Rahman, M. Z. A., & Anwar, U. M. K. (2012). Characterization of sugar palm (Arenga pinnata) fibres Tensile and thermal properties. *Journal of Thermal Analysis and Calorimetry*, *109*(2), 981–989. https://doi.org/10.1007/s10973-011-1785-1

Jawaid, M., & Abdul Khalil, H. P. S. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*, *86*(1), 1–18. https://doi.org/10.1016/j.carbpol.2011.04.043

Jonoobi, M., Harun, J., Shakeri, A., Misra, M., & Oksman, K. (2009). Chemical composition, crystallinity, and thermal degradation of bleached and unbleached kenaf bast (Hibiscus cannabinus) pulp and nanofibers. *BioResources*, *4*(2), 626–639. https://doi.org/10.15376/biores.4.2.626-639

Jumaidin, R., Sapuan, S. M., Jawaid, M., Ishak, M. R., & Sahari, J. (2017). Characteristics of Eucheuma cottonii waste from East Malaysia: physical, thermal and chemical composition. *European Journal of Phycology*, *52*(2), 200–207. https://doi.org/10.1080/09670262.2016.1248498

Kaliyan, N., & Morey, R. V. (2010). Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass.

Bioresource Technology, *101*(3), 1082–1090. https://doi.org/10.1016/j.biortech.2009.08.064

Kasim, A. N., Selamat, M. Z., Daud, M. A. M., Yaakob, M. Y., Putra, A., & Sivakumar, D. (2016). Mechanical properties of polypropylene composites reinforced with alkaline treated pineapple leaf fibre from Josapine cultivar. *International Journal of Automotive and Mechanical Engineering*, *13*(1), 3157–3167. https://doi.org/10.15282/ijame.13.1.2016.3.0263

Khalil, H. P. S. A., Ismail, H., Rozman, H. D., & Ahmad, M. N. (2001). Effect of acetylation on interfacial shear strength between plant fibres and various matrices. *European Polymer Journal*, *37*(5), 1037–1045. https://doi.org/10.1016/S0014-3057(00)00199-3

Lomelí-Ramírez, M. G., Kestur, S. G., Manríquez-González, R., Iwakiri, S., De Muniz, G. B., & Flores-Sahagun, T. S. (2014). Bio-composites of cassava starch-green coconut fiber: Part II - Structure and properties. *Carbohydrate Polymers*, *102*(1), 576–583. https://doi.org/10.1016/j.carbpol.2013.11.020

M. O. Syafiq, R., Sapuan, S. M., & Zuhri, M. R. M. (2020). Effect of cinnamon essential oil on morphological, flammability and thermal properties of nanocellulose fibre–reinforced starch biopolymer composites. *Nanotechnology Reviews*, *9*(1), 1147–1159. https://doi.org/10.1515/ntrev-2020-0087

Madineni, M. N., Faiza, S., Surekha, R. S., Ravi, R., & Guha, M. (2012). Morphological, structural, and functional properties of maranta (Maranta arundinacea L) starch. *Food Science and Biotechnology*, *21*(3), 747–752. https://doi.org/10.1007/s10068-012-0097-y

Mandal, A., & Chakrabarty, D. (2011). Isolation of nanocellulose from waste sugarcane bagasse (SCB) and its characterization. *Carbohydrate Polymers*, *86*(3), 1291–1299. https://doi.org/10.1016/j.carbpol.2011.06.030

Moshi, A. A. M., Ravindran, D., Bharathi, S. R. S., Indran, S., Saravanakumar, S. S., & Liu, Y. (2020). Characterization of a new cellulosic natural fiber extracted from the root of Ficus religiosa tree. *International Journal of Biological Macromolecules*, *142*, 212–221. https://doi.org/10.1016/j.ijbiomac.2019.09.094

Nasser, R. A., Salem, M. Z. M., Hiziroglu, S., Al-Mefarrej, H. A., Mohareb, A. S., Alam, M., & Aref, I. M. (2016). Chemical analysis of different parts of date palm (Phoenix dactylifera L.) using ultimate, proximate and thermo-gravimetric techniques for energy production. *Energies*, *9*(5). https://doi.org/10.3390/en9050374

Nazrin, A., Sapuan, S. M., Zuhri, M. Y. M., Tawakkal, I. S. M. A., & Ilyas, R. A. (2021). Water barrier and mechanical properties of sugar palm crystalline nanocellulose reinforced thermoplastic sugar palm starch (TPS)/poly(lactic acid) (PLA) blend bionanocomposites. *Nanotechnology Reviews*, *10*(1), 431–442. https://doi.org/10.1515/ntrev-2021-0033

Nogueira, G. F., Fakhouri, F. M., & de Oliveira, R. A. (2018). Extraction and characterization of arrowroot (Maranta arundinaceae L.) starch and its application in edible films. *Carbohydrate Polymers*, *186*(December 2017), 64–72. https://doi.org/10.1016/j.carbpol.2018.01.024

Nogueira, G. F., Soares, C. T., Cavasini, R., Fakhouri, F. M., & de Oliveira, R. A. (2019). Bioactive films of arrowroot starch and blackberry pulp: Physical, mechanical and barrier properties and stability to pH and sterilization. *Food Chemistry*, *275*(April 2018), 417–425. https://doi.org/10.1016/j.foodchem.2018.09.054

Oliveira Filho, J. G. de, Bezerra, C. C. de O. N., Albiero, B. R., Oldoni, F. C. A., Miranda, M., Egea, M. B., Azeredo, H. M. C. de, & Ferreira, M. D. (2020). New approach in the development of edible films: The use of carnauba wax micro- or nanoemulsions in arrowroot starch-based films. *Food Packaging and Shelf Life*, *26*(July), 100589. https://doi.org/10.1016/j.fpsl.2020.100589

Othman, N., Azahari, N. A., & Ismail, H. (2011). Thermal Properties of Polyvinyl Alcohol (PVOH)/Corn Starch Blend Film. *Malaysian Polymer Journal*, *6*(2), 147–154.

Raja, M. K. C., & Sindhu, P. (2000). Properties of Steam-Treated Arrowroot (Maranta arundinacea) Starch. *Starch - Stärke*, *52*(12), 471–476. https://doi.org/10.1002/1521-379X(200012)52:12<471::AID-

Razali, N., Salit, M. S., Jawaid, M., Ishak, M. R., & Lazim, Y. (2015). A study on chemical composition, physical, tensile, morphological, and thermal properties of roselle fibre: Effect of fibre maturity. *BioResources*, *10*(1), 1803–1823. https://doi.org/10.15376/biores.10.1.1803-1824

Saba, N., Md. Tahir, P., Abdan, K., & Ibrahim, N. A. (2015). Preparation and characterization of fire retardant nano-filler from oil palm empty fruit bunch fibers. *BioResources*, *10*(3), 4530–4543. https://doi.org/10.15376/biores.10.3.4530-4543

Sabaruddin, F. A., Paridah, M. T., Sapuan, S. M., Ilyas, R. A., Lee, S. H., Abdan, K., Mazlan, N., Roseley, A. S. M., & Abdul Khalil, H. P. S. (2020). The Effects of Unbleached and Bleached Nanocellulose on the Thermal and Flammability of Polypropylene-Reinforced Kenaf Core Hybrid Polymer Bionanocomposites. *Polymers*, *13*(1), 116. https://doi.org/10.3390/polym13010116

Sain, M., & Panthapulakkal, S. (2006). Bioprocess preparation of wheat straw fibers and their characterization. *Industrial Crops and Products*, *23*(1), 1–8. https://doi.org/10.1016/j.indcrop.2005.01.006

Sandoval Gordillo, C. A., Ayala Valencia, G., Vargas Zapata, R. A., & Agudelo Henao, A. C. (2014). Physicochemical characterization of arrowroot starch (maranta arundinacea linn) and glycerol/arrowroot starch membranes. *International Journal of Food Engineering*, *10*(4), 727–735. https://doi.org/10.1515/ijfe-2014-0122

Sapuan, S. M., Aulia, H. S., Ilyas, R. A., Atiqah, A., Dele-Afolabi, T. T., Nurazzi, M. N., Supian, A. B. M., & Atikah, M. S. N. (2020). Mechanical properties of longitudinal basalt/woven-glass-fiber-reinforced unsaturated polyester-resin hybrid composites. *Polymers*, *12*(10), 1–14. https://doi.org/10.3390/polym12102211

Saravanakumar, S. S., Kumaravel, A., Nagarajan, T., Sudhakar, P., & Baskaran, R. (2013). Characterization of a novel natural cellulosic fiber from Prosopis juliflora bark. *Carbohydrate Polymers*, *92*(2), 1928–1933.

Tarique, J., Sapuan, S. M., & Khalina, A. (2021). Effect of glycerol plasticizer loading on the physical, mechanical, thermal, and barrier properties of arrowroot (Maranta arundinacea) starch biopolymers. *Scientific Reports*, *11*(1), 13900. https://doi.org/10.1038/s41598-021-93094-y

Tarique, J., Sapuan, S. M., Khalina, A., Sherwani, S. F. K., Yusuf, J., & Ilyas, R. A. (2021). Recent developments in sustainable arrowroot (Maranta arundinacea Linn) starch biopolymers, fibres, biopolymer composites and their potential industrial applications: A review. *Journal of Materials Research and Technology*, *13*, 1191–1219. https://doi.org/10.1016/j.jmrt.2021.05.047

Wang, W. ming, Cai, Z. sheng, Yu, J. yong, & Xia, Z. peng. (2009). Changes in composition, structure, and properties of jute fibers after chemical treatments. *Fibers and Polymers*, *10*(6), 776–780. https://doi.org/10.1007/s12221-009-0776-3

Wu, C. S. (2018). Enhanced Interfacial Adhesion and Characterisation of Recycled Natural Fibre-Filled Biodegradable Green Composites. *Journal of Polymers and the Environment*, *26*(7), 2676–2685. https://doi.org/10.1007/s10924-017-1160-9

Wu, C. S., & Liao, H. T. (2017). Interface design and reinforced features of arrowroot (Maranta arundinacea) starch/polyester-based membranes: Preparation, antioxidant activity, and cytocompatibility. *Materials Science and Engineering C*, *70*, 54–61. https://doi.org/10.1016/j.msec.2016.08.067

Yang, H., Yan, R., Chen, H., Lee, D. H., & Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, *86*(12–13), 1781–1788. https://doi.org/10.1016/j.fuel.2006.12.013

Yang, J., Ching, Y., & Chuah, C. (2019). Applications of Lignocellulosic Fibers and Lignin in Bioplastics: A Review. *Polymers*, *11*(5), 751. https://doi.org/10.3390/polym11050751

Yilmaz, N. D. (2013). Effects of enzymatic treatments on the mechanical properties of corn husk fibers. *Journal of the Textile Institute*, *104*(4), 396–406. https://doi.org/10.1080/00405000.2012.736707

Yusriah, L., Sapuan, S. M., Zainudin, E. S., & Mariatti, M. (2014). Characterization of physical, mechanical, thermal and morphological properties of agro-waste betel nut (Areca catechu) husk fibre. *Journal of Cleaner Production*, *72*, 174–180. https://doi.org/10.1016/j.jclepro.2014.02.025