



Faculty of Engineering

**Physico-Mechanical, Morphological and Thermal Analysis Of Bioplastic
Films Fabricated from Sago Pith Waste Cellulose Fibres**

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**Physico-Mechanical, Morphological and Thermal Analysis Of Bioplastic
Films Fabricated from Sago Pith Waste Cellulose Fibres**

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

In light of the growing demand for sustainable alternatives to traditional plastics and the world's mounting environmental problems, this research explores the field of bioplastics with an emphasis on sago pith waste (SPW). The growing demand for biodegradable materials makes it essential to utilise resources such as SPW, which are plentiful in biomass, especially from the sago industry in Sarawak. The extraction of sago starch has led to significant environmental issues due to inadequate waste management practices. Therefore, while focusing on utilizing SPW, this research aims to fabricate a bioplastic film from SPW and investigate the optimal mass of cellulose fibres (CF) extracted from SPW solubilized in 20 mL of trifluoroacetic acid (TFA) to form a bioplastic film with good properties. First, to extract CF, the SPW underwent alkaline treatment and bleaching treatment. Then, CF was solubilized in TFA, with varying in mass from 0.10 g to 0.70 g. After the CF was fully dissolved, the process was then followed by solvent casting. The resulting bioplastic films produced were transparent with slight brown coloration. The SEM data revealed that bubble-shape protrusions on the bioplastic films appeared to shrink as the mass of CF decrease and a slight decrease in the number of visible pores were noted. Due to the improved morphological properties of the film, the tensile strength of BF-0.70 was enhanced by 90% as compared to BF-0.10. BF-0.70 also exhibited the best thermal stability as the main component of the bioplastic film started to degrade at 193°C and had the most amount of char residue. Out of all the other films, BF-0.70 also possessed the least water absorption ability, with a value of 86%, which was a good decrease from the 198% water absorption by BF-0.10. Thus, it was possible to determine the suitable CF mass. As evidenced by the features of BF-0.70, the results had proven that 0.70 g is the

optimal mass of CF that can be solubilised in TFA to form a bioplastic film with good properties.

Keywords: Sago pith waste, TFA, alkaline treatment, solvent casting, FTIR, water absorption

Analisis Fiziko-Mekanikal, Morfologi dan Termal Filem Bioplastik yang Dihasilkan daripada Serat Selulosa Hampas Sagu

ABSTRAK

Dalam usaha untuk memenuhi permintaan yang semakin meningkat terhadap alternatif yang lestari kepada plastik tradisional dan masalah alam sekitar yang semakin serius, kajian ini meneroka bidang bioplastik dengan penekanan kepada hampas sagu. Permintaan yang meningkat terhadap bahan biodegradasi menjadikan penggunaan sumber seperti hampas sagu, yang banyak terdapat dalam biojisim, amat penting terutamanya dari industri sagu di Sarawak. Pengekstrakan kanji sagu telah menyebabkan isu alam sekitar yang ketara akibat daripada amalan pengurusan sisa yang tidak lengkap. Oleh itu, dengan memberi tumpuan kepada penggunaan hampas sagu, kajian ini bertujuan untuk menghasilkan filem bioplastik daripada hampas sagu dan menyiasat jisim serat selulosa yang optimum diekstrak daripada hampas sagu yang dilarutkan dalam 20 mL asid trifluoroasetik (TFA) untuk membentuk filem bioplastik dengan sifat yang cemerlang. Pertama sekali, untuk mengekstrak serat selulosa, SPW telah melalui rawatan alkali dan rawatan pelunturan. Kemudian, serat selulosa dilarutkan dalam TFA, dengan variasi jisim dari 0.10 g hingga 0.70 g. Setelah serat selulosa larut sepenuhnya, proses diteruskan dengan pengacuan pelarut. Filem bioplastik yang terhasil adalah lutsinar dengan sedikit pewarnaan coklat. Data SEM mendedahkan bahawa bonjolan berbentuk gelembung pada filem bioplastik kelihatan mengecut apabila jisim serat selulosa berkurangan dan sedikit pengurangan dalam bilangan liang yang kelihatan telah diperhatikan. Disebabkan oleh penambahbaikan sifat morfologi filem tersebut, kekuatan tegangan BF-0.70 meningkat sebanyak 90% berbanding dengan BF-0.10. BF-0.70 juga mempamerkan kestabilan terma terbaik kerana komponen utama filem bioplastik mula terurai pada 193°C dan mempunyai

sisia arang paling banyak. Daripada semua filem lain, BF-0.70 juga mempunyai kebolehan penyerapan air yang paling rendah, dengan nilai 86%, yang merupakan penurunan yang baik daripada penyerapan air sebanyak 198% oleh BF-0.10. Oleh itu, jisim serat selulosa yang terbaik telah dijumpai. Seperti yang dibuktikan oleh ciri-ciri BF-0.70, keputusan telah membuktikan bahawa 0.70 g adalah jisim serat selulosa yang boleh dilarutkan dalam TFA untuk membentuk filem bioplastik dengan sifat yang baik.

Kata kunci: *Hampas sagu, TFA, rawatan alkali, FTIR, pencelupan pelarut, keupayaan penyerapan air*

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LIST OF ABBREVIATIONS

BF	Bioplastic film
BPA	Bisphenol A
CF	Cellulose fibres
CGS	Centre for Graduate Studies
CRAUN	Crop Research and Application Unit
DoA	Department of Agriculture
EDX	Energy dispersive X-ray
EMBL-EBI	European Molecular Biology Laboratory–European Bioinformatics Institute
FTIR	Fourier transform infrared
FTIR-ATR	Fourier transform infrared attenuated total reflectance
GDP	Gross domestic product
HDPE	Polyethylene high density
LDPE	Polyethylene low density
MCC	Microcrystalline cellulose
NOAA	National Oceanic and Atmospheric Administration
OECD	Organisation for Economic Co-operation and Development
OSL	Ocean surface layer
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PVC	Poly(vinyl) chloride

SEM	Scanning electron microscope
SPW	Sago pith waste
SSCMF	Sago starch filled with cellulose microfibrils
TFA	Trifluoroacetic acid
TFAA	Trifluoroacetic anhydride
TGA	Thermogravimetric analysis
TS	Tensile strength
UN	United Nations
UNIMAS	Universiti Malaysia Sarawak

CHAPTER 1

INTRODUCTION

1.1 Study Background

The consumption of fossil fuels for energy and manufacturing processes has led to the rapid depletion of these non-renewable resources, significantly impacting the environment. Today, petroleum is the main source of plastic, with approximately one-fourth of each barrel of oil used to produce plastics and other goods (Marrone, 2022). In 2022, over 390 million tonnes of fossil fuel-based plastics were manufactured, contributing to a severe global plastic pollution problem (Ali et al., 2023). This pollution poses serious threats to both human and ecological health, necessitating the urgent need for sustainable alternatives.

In response to these challenges, the development of sustainable materials such as bioplastics has gained considerable attention. Bioplastics, derived from renewable biomass sources, offer a promising alternative to conventional plastics made from fossil fuels (Filho et al., 2022). They not only reduce the dependency on finite fossil resources but also provide potential solutions for waste management issues. Some bioplastics are highly biodegradable, contributing to more environmentally sustainable practices and reducing the environmental footprint associated with plastic waste (Lamberti et al., 2020). Implementing bioplastics could significantly mitigate soil, water, and air pollution, aligning with global efforts to adopt more sustainable and eco-friendly practices.

Despite their potential, the production of bioplastics faces several obstacles, primarily due to higher production costs, which are two to three times more expensive than

traditional plastics and has lower production yields. Additionally, the manufacturing process encounters various difficulties. For example, some bioplastics possess inferior mechanical properties, making them more brittle and prone to tearing compared to oil-based plastics. Furthermore, bioplastics often have weaker barrier properties than conventional plastics, resulting in a shorter lifespan. Despite these challenges, ongoing efforts aim to enhance the production processes and mechanical properties of bioplastics, making them a more feasible alternative to conventional plastics (Ibrahim et al., 2021).

One such effort involves creating bioplastics from agricultural waste such as sago pith waste (SPW). The utilization of SPW as a raw material for bioplastic production holds great promise in addressing both waste management and sustainable resource utilization. Nevertheless, raw SPW cannot be used to produce higher value-added materials because of the composition of the waste. Previous research demonstrated that starch had been extracted from SPW with the assistance of ultrasound to form bioplastic (Tan et al., 2021) and CF can be extracted from treating SPW through alkaline treatment and bleaching treatment. Yacob and his team treated SPW by using alkaline and bleaching treatment to extract CF to act as a reinforcing agent, specifically to improve the properties of starch films produced in the study (Yacob et al., 2018). Meanwhile, Jampi and her team also used similar techniques to extract CF from SPW, before preparing it into hydrogel (Jampi et al., 2021).

Building on these findings, treatments to extract CF were applied in this study, as past research has used cellulose-based raw materials to form bioplastic films by solubilizing them in trifluoroacetic acid (TFA) and solvent casting (Bilo et al., 2018). A method discovered by Bayer and his team uses trifluoroacetic acid (TFA) as a solvent to

solubilize cellulose and similar compounds as well as several agricultural plant wastes to form bioplastic films (Tedeschi et al., 2020). TFA aids in the formation of a homogenous solution that can be cast into a bioplastic film. Due to its ability to swell cellulose effectively and its ability to be recycled because of its low boiling point, trifluoroacetic acid (TFA) is of interest since it offers an effective method to reduce cellulosic crystallinity and break up hydrogen bonds within the crystalline region (Liu et al., 2021)

While TFA has shown promise in creating bioplastics from various sources, such as rice hulls, green herbs, cocoa pod husks, and seaweed (Farid et al., 2021), a substantial research gap persists. Currently, there is no research that uses CF extracted from SPW to produce bioplastic films by using TFA. Furthermore, there is a lack of investigation into identifying the mass of cellulose fibres (CF) needed from SPW in a fixed volume of TFA to form a bioplastic film. Consequently, the influence of CF mass on critical properties of resulting bioplastic films including morphology, mechanical strength, thermal characteristics, and water absorption remains unexplored. Addressing this gap is crucial for optimizing the production process and enhancing the overall performance of bioplastic films.

Therefore, the research focuses on addressing this research gap by investigating the effects of the different masses of CF in a fixed volume of TFA on the properties of the resulting bioplastic films. In addition, the FTIR, morphological, mechanical, and thermal properties as well as water absorption of bioplastic films produced were also analysed.

1.2 Problem Statement

The main problem of the research is the significant environmental challenges posed by the improper waste management of SPW generated from sago starch extraction in

Sarawak, where 90% of the world's sago starch is produced. Despite the abundance of SPW, its inefficient handling leads to severe water and air pollution. This research addresses the need for sustainable solutions by focusing on the extraction and utilization of CF from SPW to produce bioplastic films. The critical research gap lies in investigating the mass of CF that can be solubilized in a fixed volume of TFA to enhance the morphological, mechanical, and thermal properties, as well as water absorption capabilities, of the resulting bioplastic films.

1.3 Hypothesis

The combination of alkali and bleaching treatments of SPW will effectively extract CF suitable for bioplastic film formation. It is hypothesized that the mass of CF solubilized in 20 mL of TFA will significantly influence the properties of the resulting bioplastic films. Among the varying masses of CF, 0.70 g of CF is expected to yield a bioplastic film with good properties, including enhanced tensile strength, improved thermal stability, and reduced water absorption.

1.4 Objectives

The research's objectives include:

- i. To extract cellulose fibres from SPW for bioplastic production.
- ii. To investigate the mass of CF used in forming bioplastic films per 20 mL of TFA.

1.5 Scope of Study

This study focuses on the sustainable utilization of SPW from the sago industry in Sarawak to address significant environmental challenges caused by improper waste management. The scope of the research encompasses the following key areas:

i. Extraction of Cellulose Fibres (CF):

Implementing alkali and bleaching treatments on SPW to extract CF, transforming waste into a valuable raw material suitable for bioplastic film production.

ii. Solubilization and Bioplastic Film Formation:

Investigating the solubilization of CF in TFA at varying masses (0.10 g to 0.70 g) to form bioplastic films as well as utilizing solvent casting to produce bioplastic films and examining their physical appearance.

iii. Characterization of Bioplastic Films:

- a. Performing Fourier Transform Infrared Spectroscopy (FTIR) analysis to study chemical compositions and functional groups present in the bioplastic films.
- b. Conducting morphological analysis using Scanning Electron Microscopy (SEM) to observe structural properties and pore distribution.
- c. Evaluating mechanical properties such as tensile strength to determine the film's durability and robustness.
- d. Assessing thermal stability through thermal degradation tests to determine the film's resistance to heat.
- e. Measuring water absorption capacity to understand the film's potential for applications requiring moisture resistance.

This research hopes to contribute to sustainable waste management practices by converting SPW into high-value bioplastic films, thus mitigating environmental pollution and promoting the development of biodegradable materials.

CHAPTER 2

LITERATURE REVIEW

2.1 Polymers

A polymer is a material, either natural or synthetic, made up of extremely large molecules called macromolecules. These macromolecules are formed by linking together many smaller units called monomers. Polymers are abundant in biological organisms and include substances such as proteins, cellulose, and nucleic acids (Rial, 2022).

2.1.1 Types of Polymers

Based on their synthesis, polymers can be classified into two types: synthetic and natural as discussed in Chapter 2.2 and 2.3.

2.2 Synthetic Polymers

Synthetic polymers are built with long chains of atoms and put together in repeating units, usually way longer than the polymers that occur in nature. Therefore, synthetic polymer is sturdy, lightweight, and elastic due to the length of the chains and their arrayed patterns. Synthetic polymers are very useful due to their properties, causing excellent growth of in the production of plastic, beating many other man-made materials (Davoodi et al., 2024).

The word plastic originally meant “pliable and easily shaped”. Humans have learned to manufacture plastic over 150 years ago, regularly using the plentiful carbon atoms obtained from petroleum and fossil fuel (Davoodi et al., 2024). Plastic is an amazing material that stimulates economic growth and boosts modern advancements through its synthetic properties. They are a valuable resource that offer numerous advantages to

civilisation, including improving their well-being, cleanliness, and safety. Moreover, plastic materials have played a vital role in multiple industries, such as food packaging, drug delivery, fuel production, disease prevention, and road construction. In 2019, the packaging sector had dominated the plastic market, with building and construction, textiles, automotive and transportation, infrastructure and construction, and consumer goods tailing closely behind (Kumar et al., 2021).

2.2.1 Addition Polymers

Plastics are normally made from addition polymers, as it results in strong and durable materials that can be moulded into a wide range of shapes and sizes. Addition polymerization, which is also known as chain reaction polymerization, necessitate that the monomers possess no less than one double bond. Both molecules and by-products are neither removed nor created in this type of polymerization (Youssef, 2022).

The monomers had been joined through addition reaction and no atoms have been lost (Youssef, 2022). Additionally, most polymers are composed of many different types of molecules such as thousands of monomer units that can be found along HDPE molecules. The common addition polymers can be observed in Table 2.1.

Table 2.1: Common Addition Polymers (Reusch, 2021)

Name(s)	Formula	Monomer	Properties	Usage
Polyethylene low density (LDPE)	$-(CH_2-CH_2)_n-$	ethylene $CH_2=CH_2$	Soft, waxy solid	Film wraps, plastic bags
Polyethylene high density (HDPE)	$-(CH_2-CH_2)_n-$	ethylene $CH_2=CH_2$	Rigid, translucent solid	electrical insulation bottles, toys
Polypropylene (PP) different grades	$-[CH_2-CH(CH_3)]_n-$	propylene $CH_2=CHCH_3$	<u>atactic</u> : soft, elastic solid <u>isotactic</u> : hard, strong solid	similar to LDPE carpet, upholstery
Poly (vinyl chloride) (PVC)	$-(CH_2-CHCl)_n-$	vinyl chloride $CH_2=CHCl$	strong rigid, solid	pipes, siding, flooring
Polystyrene (PS)	$-[CH_2-CH(C_6H_5)]_n-$	styrene $CH_2=CHC_6H_5$	hard, rigid, clear solid, soluble in organic solvents	toys, cabinets packaging (foamed)

2.2.2 Global Plastics Production

Plastic is excellently multipurpose, compliant, has low density, able to resist moisture and robust, thus making it ideal in various application. The price is also mainly cheap and affordable (Berry et al., 2023). The growth of global population and consumption, urbanization, and industrialization have also contributed to the increasing demand for plastics. Therefore, according to The Organization for Economic Cooperation and Development's (OECD) primary Global Plastics Outlook: Economic Drivers, Environmental Impacts, and Policy Options report written in February 2022, the production of plastics has skyrocketed by 230 times, increasing from 2 million tonnes in

1950 to 460 million tonnes in 2019 as observed in Figure 2.1. It was also reported that the COVID-19 pandemic that took place in 2020 had a brief impact on the previous trends of plastics production. The global usage of plastics declined by 2.2% due to reduced economic activity, even though the usage of particular plastics applications, such as personal protective equipment, soared significantly during the pandemic. Nevertheless, as economic activity recovered, the rising trajectory of plastics production and waste generation resumed in 2021 (OECD, 2022).

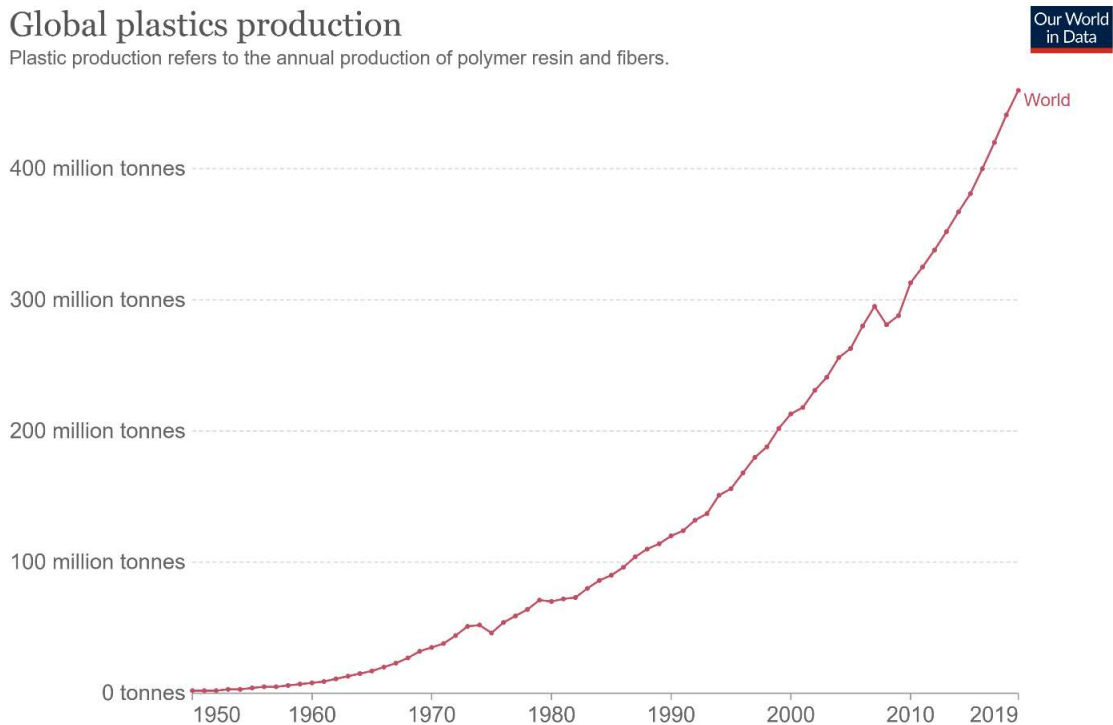


Figure 2.1: Global Plastics Production (OECD, 2022)

2.2.3 Environmental Issues

It is discussed in Chapter 2.2.2 that the number of plastics has increased significantly throughout the years. This is followed by a serious environmental issue that it caused as the plastics are very durable and tend to degrade slowly. Huge numbers of

plastics are disposed yearly, hence contaminating lands, streams, coasts, seashores, and oceans, thus posing huge threats to humans and other living things. This is because the population has acquired a “disposable” lifestyle, in which around 50% of the plastics are only used once and then thrown away (Berry et al., 2023).

Plastics are often made up of monomers such as ethylene and propylene derived from fossil hydrocarbons, which means that most of the plastics are non-biodegradable. Due to this, it is quite challenging to achieve an optimal circular economy, which is an economic model to minimize waste. Unfortunately, the current reality for most plastic materials is a linear lifecycle, where only 12% of them going through incineration and 9% end up in recycling centres. The remainder either wind up in landfills or into the environment (Rosenboom, Langer, & Traverso, 2022). This leads to water pollution, land pollution and air pollution.

2.2.3.1 Water Pollution (Marine Debris)

Le Guern (2019) claims that for the previous 25 years, materials that were abandoned or lost into the water have been referred to as "marine debris." Marine debris typically consists of plastics, metals, glass, and other materials like rubber or textiles. Since most plastics enter the oceans through coastlines, rivers, tides, and marine sources, they do make up a significant portion of the floating litter. Due to the buoyancy of most plastics, the dispersion and accumulation of ocean plastics can be easily influenced by surface currents and wind patterns. The plastics end up accumulating in oceanic gyres, with higher concentrations of plastics at the ocean basins' centre and considerably lower amounts around the perimeters (Kibria et al., 2023). A study done regarding the plastics concentration in the ocean surface layer (OSL) stated that the number has fluctuated throughout time but has climbed dramatically since 2005 (Eriksen et al. 2023). The study

estimates that around 82 to 358 trillion plastic particles were in the OSL, which weighs about 1.1 to 4.9 million tonnes. Most of them were microplastics (Eriksen et al., 2023).

Estimated decomposition rates have been stated by the Ocean Conservancy & The National Oceanic and Atmospheric Administration (NOAA) Marine Debris (2019), which can be observed in Table 2.2. Additionally, toxic chemicals such as polystyrene and bisphenol A (BPA) will be discharged into the water during degradation, instigating water pollution.

Table 2.2: Decomposition Rate of Different Type of Debris Found in Ocean (Ocean Conservancy & NOAA Marine Debris, 2019)

Type of Debris	Decomposition rate
Plastic grocery bag	10 to 20 years*
Foam cup	50 years*
Disposable diaper	450 years*
Plastic beverage bottle	450 years*
*Items are made from a type of plastic. Although no one has lived for 450 or 600 years, many scientists believe plastics never entirely go away. These decomposition rates are estimates for the time it takes for these items to become microscopic and no longer be visible.	

Animals are the living things that are most affected by marine pollution. According to Alabi et al. (2019), they are typically exposed to plastic waste through entanglement and, most frequently, ingestion. The animals ingested these plastics, mistaking these wastes as food, and always got entangled in plastic products such as nets, which can cause damage and deaths. Animals that eat jellyfish as their main food, such as sea turtles, repeatedly confuse discarded plastic waste with jellyfish. Sea birds also often view microplastics as cuttlefish, and fish mistake plastic for their natural prey. This can cause extreme injury to the animal's digestive system and eventually cause starvation,

malnutrition, and, lastly, death. Figure 2.2 shows a seabird corpse that swallowed plastic waste and damaged its digestive system.



Figure 2.2: Bird Corpse that Swallows Plastic (Jordan, 2009)

Furthermore, due to entanglement in plastic waste, various animals, such as birds, seals, and turtles, face death through drowning or suffocation (Alabi et al., 2019). This will cause the animals to lose their ability to catch food or escape from predators. Entanglement may also cause them to suffer from wounds and other major injuries. For example, marine animals often got caught up in discarded fishing nets, causing them to starve and eventually die, as shown in Figure 2.3. Seals and sea lions are the ones that are predominantly affected due to their inquisitive nature to investigate various objects in their environment (Johnson, 2019).



Figure 2.3: Seals Entangled in Fishing Nets (Israelson, 2010)

2.2.3.2 Land Pollution

There are huge numbers of plastic products found in human's inhabited and occupational environment. The terrestrial ecosystem can sustain significant harm due to plastics, before being transported to the aquatic environment. While there are a lot of data found regarding the plastic debris in marine habitat, data on volume of plastic wastes on land are barely found (Alabi et al., 2019).

Since landfilling is a popular way to dispose plastic waste at its end-of-life, many environmental impacts may result. For example, leachate and gases produced by landfills are results of biological, chemical, and physical processes. This leads to the release of particles such as microplastics to the environment via air or leachate which causes pollution (Wojnowska-Baryła et al., 2022). The ecosystem could also be polluted by toxic chemicals that are leached out from chlorinated plastics. The toxic chemicals penetrate soils and then reach underground water or nearby aquatic system (Alabi et al., 2019).

Additionally, sewage sludge is one of the crucial factors of microplastics distribution in soils. Sewage sludge can act as a fertilizer; therefore, it is always distributed to fields as shown in Figure 2.4 and thousands of tonnes of soils are contaminated with microplastics (Hooge et al., 2023).



Figure 2.4: Sewage Sludge Distributed to Fields (UN Environment Programme, 2018)

2.2.3.3 Air Pollution

One of the main impacts of plastic production and usage is air pollution. Ecology is negatively affected by various chemicals released by plastics during degradation. Based on a study conducted by Royer et al. (2018), the most frequently used plastics emits two greenhouse gases, methane (CH_4) and ethylene (C_2H_4), if exposed to ambient solar radiation. The most prolific emitter of both gases is polyethylene, a synthetic polymer that is mostly generated and discarded worldwide. Moreover, the gas production rate is most likely to increase if more plastics of larger surface area are manufactured. The plastics material exposed to full sunlight is also more than the ones that are submerged. This is

dangerous as the study carried out by Royer et al. (2018) found that greater emissions of hydrocarbon usually occur if the plastics are exposed to air especially in warmer climate rather than the plastics underwater. According to scientific research, human health is in danger due to localized air pollution and the release of toxins that took place during the process of plastic shredding and melting. These risks include exposure to fine particles, dioxins, volatile organic compounds, and other harmful chemical additives present in plastics. These have been linked with respiratory illnesses, asthma, cancer, and damage to the reproductive system (Human Rights Watch, 2022).

2.2.4 Preventive Measures and Alternatives

Preventive measures need to be intensively taken to reduce negative impacts the discarded plastics brought to the environment. One example is some cities in Sarawak have established their waste management practices and has launched a campaign called ‘No Plastic Everyday’, with hopes to bring positive environmental changes (The Borneo Post, 2019). Malaysia, as a whole, aims to execute a plastic bag ban in 2025, but this plan has received mixed reviews from the public (Alias, 2023).

Another known method is via recycling, a process which collects separated waste discarded by consumers or centres, undergo multiple stages and in the end, generates it to plastics with various qualities as a result (Prata et al., 2019). When compared to landfilling or incineration, recycling plastic waste is a more energy and environmentally friendly approach. The reason behind this is that the incineration plants are expensive to build, and even with air pollution filtering technologies, importing plastic waste is frequently required to ensure a steady supply of raw material for economically viable incineration plant operations (Chen et al., 2021).

Plastics can also be converted into feedstocks by using energy-intensive processes to recover constituents that can be used to generate fuels such as gasoline (Prata et al., 2019). This is due to the high energy density of hydrocarbons that are present in plastic, making it an amazing source of fuel. Therefore, plastic pyrolysis and combustion introduce a reasonably priced and environmentally friendly end-of-life solution, while also enabling the manufacture of value-added products (Padmanabhan et al., 2022).

Another alternative that is now quite common is bioplastic. Multiples research have been conducted to investigate the proper materials and methods to produce a proper bioplastic.

2.3 Biopolymers and Bioplastics

Derived from the Greek words’ “bio” and “polymer”, biopolymers mean nature and many parts, respectively. Biopolymers are natural organic substances that are derived from living organisms. Biopolymers are the most common type of macromolecules, which are made up of large molecules with many repeating subunits. Biopolymers consist of nucleic acids, proteins, carbohydrates, and large non-polymeric molecules such as lipids and macrocycles. These types of macromolecules are the most frequently found in nature (Baranwal et al., 2022). They are highly suitable for the manufacture of biodegradable and bio-based bioplastics as these biopolymers possess the necessary physicochemical, thermal, and mechanical properties (Faizan Muneer et al., 2021).

From applications that range from food processing and agriculture to compost bags and sanitation, bioplastics have become a crucial requirement in numerous industrial sectors. In terms of performance metrics, bioplastics nonetheless are still lacking when compared to synthetic plastics. As a result, extensive research is currently underway to

explore novel green polymer materials that can sustain the increasing demand for biodegradable and bio-based polymers (Ibrahim et al., 2021).

2.3.1 Classifications of Bioplastics

Even if the plastics are derived from biomass, this does not indicate that the plastic is biodegradable. According to Nanda et al. (2022), there are two major types of bioplastics, which are biodegradable plastics and bio-based plastic.

i. Biodegradable plastic

Biodegradable plastics stress on the disposal or ‘end-of-life’ processes and does not produce plastics from carbon sources. For plastic biodegradability, the key factor is the timescale (given certain conditions) to avoid solid waste build-up in the environment. This is because all plastics can biodegrade even if it takes a long time, sometimes for centuries. The most common fossil fuel biodegradable plastics are polybutylene succinate, polycaprolactone, polybutyrate adipate terephthalate and polyvinyl alcohol.

ii. Bio-based plastic

The origin of carbon atom constituents is emphasized in this type of plastic and does not take count of the disposal procedures. According to Association of Plastics Manufacture (2019), bio-based plastics are made in whole or partially from renewable biological resources. For example, polylactic acid (PLA) is produced from lactic acid processed from starch.

The terms "bio-based" and "biodegradable" are often used interchangeably, but this is not accurate as they have different meanings. Bio-based plastics can be made from non-petroleum biological resources, while biodegradable plastics are manufactured from either bio-based or petroleum-based materials and when given exposure to naturally occurring

bacteria, will disintegrate. It is worth noting that not all bio-based plastics are biodegradable, and the term "biobased" only relates to the material's manufacturing process, not its eventual fate (Moshood et al., 2022).

2.3.2 Types of Bioplastics

There are many past and ongoing research carried out to study the processability of the 'new' biodegradable bioplastics such as PLA, PHAs and starch-, cellulose- and protein-based materials.

2.3.2.1 Polylactic Acid (PLA)

A specific type of bacteria called *Lactobacillus*, which has been optimized for this particular procedure, help ferments carbohydrates, which are typically found in inexpensive source such as corn, to produce lactic acid. Polylactic acid offers numerous advantages, including being made from agricultural products, assisting in the reduction of greenhouse gas emissions by absorbing a significant amount of carbon dioxide (CO₂), only requiring less energy during processing, and having tuneable physical and mechanical properties through material modifications (Ranakoti et al., 2022). Since PLA is biodegradable, there are a lot of end-of-life solutions alternatives, namely landfilling, chemical and mechanical recycling, as well as industrial composting (Rezvani Ghomi et al., 2021).

2.3.2.2 Polyhydroxyalkanoates (PHA)

Through extraction and refining procedures, PHAs can be extracted from several kinds of bacteria. PHAs are typically made by microscopic organisms within cells and retained as carbon and energy in unique parts of the cell called carbonosomes, which happens when they don't have enough nutrients available (Acharjee et al., 2022). PHA polymers are known for its hydrophobicity, being water-insoluble, and being difficult to

break down. Additionally, they also have piezoelectric properties and are better than polypropylene at resisting damage from UV light. PHA polymers, however, tend to be less elastic and more brittle than other materials like polypropylene and polyethylene. PHA polymers offer a variety of characteristics overall, but their greatest benefit is that it is possible for them to degrade completely. PHA polymers offer a variety of characteristics overall, but their greatest benefit is that it is possible for them to degrade completely (Kaniuk & Stachewicz, 2021).

2.3.3 Bioplastic Characterisation

It is crucial to characterise bioplastic films to understand their characteristics and behaviour. Researchers are able to study more on how these materials will function in diverse applications by examining the chemical composition, mechanical properties, thermal stability, and other aspects of bioplastic. The performance of bioplastic films can be improved by using this knowledge to optimize the production process. Characterization can also help in ensuring that bioplastic films fit certain requirements for the use for which they are intended.

2.3.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

A quick, inexpensive, simple, and non-destructive approach to analysis is FTIR. When molecules are subjected to infrared light at a specific wavelength, it measures the vibration and rotation of the molecules (Eid, 2022), thus providing information such as functional groups, molecular bonds, and chemical modifications present in the film (Md Salim et al., 2021). This study uses FTIR analysis to quickly, and effectively identify functional groups and identify any potential chemical alterations in the SPW after treatment and the bioplastic film samples formed (Patel et al., 2023). For example, the SPW treatment to extract cellulose changes the intensity of the OH group at range 3000 to

3500 cm⁻¹, which occurred because the alkali and bleaching treatments applied to the SPW in order to obtain CF caused the intermolecular and intramolecular hydrogen bonds that most of the hydroxyl groups formed to degrade (Abu-Thabit et al., 2020).

2.3.3.2 Scanning Electron Microscopy (SEM)

SEM, or scanning electron microscopy, is a useful technique for characterizing bioplastics. SEM is a type of microscope that forms images using electrons as opposed to light. An electron microscope can be found at the top of the microscope, which produces a beam of electrons that follows a vertical path through the microscope. The path is held within a vacuum. The beam is focused down toward the sample as it passes via electromagnetic fields and lenses. Electrons and X-rays are ejected from the sample after the beam hits it (Radiological and Environmental Management, 2019). The sample is prepared by adhering it to a metal stub by using double-sided conductive tapes such as carbon or copper tapes available in the SEM lab, coating it with a thin layer of metal (40–60 nm), such as gold, and then examining it under a microscope (Sadasivan, 2021).

For example, in the context of SPW that undergoes treatment to extract cellulose, the SEM images was used to observe the diminishing presence of starch particles that were initially present in the SPW samples. SEM images revealed the disappearance of starch granules, corroborating the effectiveness of the cellulose extraction treatment in dissolving starch in the SPW (Yang et al., 2021).

To view the surface of the sample's features and assess the surface's differences, the samples can be magnified numerous times. Moreover, SEM offers the opportunity to examine the sample at a high resolution (Ural, 2021). Therefore, any defects that are present on the surface, such as voids and cracks that could be affect the quality of the film, can be detected (Kowser et al., 2023).

2.3.3.3 Energy Dispersive X-ray (EDX) Analysis

EDX is used together with a scanning electron microscope (SEM) and can extract much more information from a sample than an SEM can alone. By directing an electron beam onto a sample, this analysis knocks off part of the electrons from the atoms' inner shells which creates a small positively charged area, called an electron hole. To fill the gaps left by the electrons that were knocked off, electrons from the atoms' outer shells move in to balance out the positive charge. These incoming outer-shell electrons emit X-rays as they release energy (Nanakoudis, 2019). Due to the unique X-ray spectra that each element emits after interacting with electrons, the elements may be identified from one another. All other elements in the sample can be identified by EDX by analysing the X-rays, apart from lithium, hydrogen, and helium (Measurlabs, 2023).

Moreover, the information obtained from this analysis can help identify the composition of the CF extracted from SPW and bioplastic or confirm any presence of additives or contaminants.

2.3.3.4 Tensile Testing

The tensile test, often known as the tensile strength test, offers a lot of details regarding the mechanical behaviour or strength of a material. A tensile test's fundamental concept is to clamp a sample of a material between two fixtures known as "grips". The length and cross-sectional area of the material are known. Then, the material is held in place by one grip while being pulled until it breaks by the other grip (Michigan Technological University, 2023). From the tensile testing, a stress-strain curve is obtained which was initially converted from force versus stroke curve. The curve represents the relationship between the applied stress (force per unit area) and the resulting strain

(relative to the original length of the sample). Each material that are tested has a distinct stress-strain curve (Iowa State University, 2021).

Initially, there is a linear relationship in the curve between the stress and strain, which means that there was no plastic deformation at this portion of the graph. This slope is called the modulus of elasticity or Young's Modulus, which is the property of the material that is deformed as it undergoes stress. However, when the stress is removed, it returns to its original shape (Iowa State University, 2021). Young's Modulus can be defined as the ratio of tensile stress (σ) to tensile strain (ϵ) as shown in Equation 2.1. From the stress-strain curve, the Young's modulus can be found by calculating the gradient of the linear slope (University of Birmingham, 2023).

$$E = \frac{\sigma}{\epsilon} = \frac{F/A}{\Delta l/l} \quad \text{Equation 2.1}$$

The maximum stress a material can withstand before breaking when it is allowed to be stretched or pulled is known as tensile strength (Pal et al., 2022). The ultimate tensile strength is the force the material withstands before it breaks into two or more pieces. The value can be calculated from the data obtained from the tensile test, by dividing the maximum force applied to the sample and the area. The units that are often use for tensile strength is megapascal (MPa) and Newton per square millimetre (N/mm²).

Finding the Young's modulus and ultimate tensile strength of bioplastic film in this research is indeed useful to predict its behaviour when force is applied, as well as determining its suitability for intended applications.

2.3.3.5 Thermogravimetric analysis (TGA)

TGA helps in measuring and calculating the amount of weight change that occurs if a sample goes through changes during heating. The process includes gradually heating a

sample with a known weight at a controlled rate. The temperature is increased steadily and at different time intervals, the changes in weight are recorded in relation to the temperature. TGA curve can be used to interpret the results as it shows the weight change based on temperature or time (Raut, 2022). The TGA curve provides valuable insights into the behaviour, composition, and characteristics of the analysed bioplastics. It reveals necessary information such as the evaporation of volatile components, decomposition of components in the bioplastics, and the final residues (Ace Laboratories, 2023).

When designing bioplastics that are meant to withstand high temperatures, TGA is crucial. This is because the devices that uses the material may fail when use repeatedly, even if there is a slight breakdown or composition of the material at the expected operating temperature. The TGA analyser's controlled environment also helps facilitates the measurement of how quickly the decomposition reaction takes place (Garcia-Herrera & Price, 2020). The sample's remaining mass after it has been heated to a high temperature and gone through thermal degradation is known as the char residue (Chen et al., 2022). Char residue is important for analysis as higher char residue yield after TGA indicates that the material is more thermally stable (Umar et al., 2022).

2.3.3.6 Water Absorption

Water absorption helps measure the amount of water absorbed by a bioplastic within a specific timeframe. It is a practical method to determine the liquid absorption capacity or resilience of bioplastic (Intertek Group, 2023) The bioplastics are normally immersed in distilled water for 24 hours at 23°C after drying in the oven at a specific temperature. The initial weight of the bioplastic is recorded as well as the final weight after immersion. The percentage of weight increase will be calculated.

Water absorption is an important analysis in evaluating bioplastics for various applications. When bioplastics are exposed to moisture, it immediately affects their performance and longevity (Intertek Group, 2023). Furthermore, water absorption can impact the bioplastic's dimensional stability, such as swelling and expansion. In addition to change in dimensions, material characteristics like mechanical strength can also be impacted by water absorption (Ensinger, 2023).

2.3.4 Application of Bioplastics

Bioplastics are used in a variety of applications across multiple industries due to their eco-friendly properties. The followings are some common applications.

Bioplastics are extensively utilized in packaging materials, including bags, containers, and food packaging. However, food packaging is probably one of the most rapidly expanding markets for plastics. Utilizing plastics is crucial for preventing food contamination and minimizing post-harvest losses. However, traditional plastic food packaging is unsustainable, whereas bioplastics, with their numerous competitive advantages, are expected to dominate global market demand. Given the current trends, food packaging is, and will likely continue to be, one of the top sectors for bioplastics (Ghasemlou et al., 2024).

In agriculture, bioplastics are used for mulch films, seed coatings, and plant pots, which help reduce plastic waste and improve sustainability in farming practices. In particular, plastic mulching is an agricultural technique that can enhance the soil microclimate and boost crop yields. The application of plastic mulch films has increased worldwide, with over 1 million tons used each year. Polyethylene (PE) films have been the primary choice because of their durability, transparency, and affordability. However, their nondegradable nature leads to plastic buildup in the soil, adversely affecting soil quality.

To address this issue, biodegradable mulch films (BMFs) made from materials like polylactic acid (PLA), polybutylene adipate terephthalate (PBAT) and polyhydroxyalkanoates (PHA) have emerged as viable alternatives (Jin et al., 2024).

Other than that, bioplastics are widely utilized in a range of biomedical applications, such as tissue engineering, scaffold design, nerve regeneration, wound healing, and drug delivery, among others (Arif et al., 2023). Specifically, significant progress in nanomedicine has resulted in the creation of drug delivery systems utilizing bioplastics. These systems provide numerous benefits, such as extended drug shelf-life, targeted delivery to specific organs or tissues, reduced frequency of therapeutic doses, enhanced drug efficacy, and fewer side effects. Among these drug delivery systems, polylactic acid (PLA) and poly(lactic-co-glycolic acid) (PLGA) nanoparticles are the most thoroughly researched due to their high drug-loading capacity, excellent biocompatibility, biodegradability, and customizable release properties (Lamparelli et al., 2023).

Textile production is continuously growing to meet the demands of fashion, style, and marketing, while also addressing increasingly competitive technical challenges. However, bioplastic textiles, made from sustainable materials such as maize, algae, or soy, present a promising solution for decreasing the fashion industry's carbon emissions and waste production (Textile Technology, 2023). For instance, a company in Italy has invented an innovative eco-fiber that revolutionizes textile concepts. Made entirely from bio-based sources like castor beans and maize waste, it offers a reduced environmental footprint along with outstanding lightness, strength, and comfort. This represents a major advancement towards a more sustainable and innovative textile industry (Fulgar, 2024).

These applications demonstrate the flexibility and eco-friendliness of bioplastics in many fields. As research progresses, bioplastics are set to become even more important in building a sustainable future.

2.3.5 Advantages and Disadvantages of Bioplastics

Due to the obvious advantages the bioplastics brings, the production of bioplastics is growing fast. These advantages listed below will grow as the oil supply tightens and causing the price to fluctuate. The fluctuating price of crude oil will make bioplastics more feasible. The demand for plastics is increasing, and it is estimated that around 10% of crude oil will be required to manufacture plastics in the coming years. Therefore, the mineral oil industry could find some relief, as the depletion of its sources may slow down without the involvement of the plastic industry (Vettkötter, 2019).

The next advantage of using bioplastics is that it can reduce the carbon footprint. Plastic manufacturing that consumes oil resulted in the release of over 850 million tonnes of CO₂ into the atmosphere in 2019, representing around 2% of global CO₂ emissions. The largest portion of CO₂ emissions associated with plastic production comes from raw material extraction (61%) and polymer production (30%), while only a small portion (9%) is attributed to the end-of-life stage, primarily from incineration (Rosenboom et al., 2022). Based on the previous researchers, results show that greenhouse gas (GHG) emissions could potentially be reduced by approximately 25% if a renewable feedstock such as sugarcane is used as a complete substitute for fossil feedstocks (Zheng & Suh, 2019). Therefore, reducing our dependence on fossil feedstocks through bioplastic film production can help in decreasing greenhouse gas emissions and advancing a more sustainable future.

In addition to reducing the carbon footprint, the production of bioplastics can bring significant economic benefits to rural communities, particularly in developing countries. Since crops are the primary source of bioplastic manufacturing, the demand for these crops is likely to increase, which will help increase income for farmers. This economic boost can have a positive impact on the livelihoods of people in these communities and help to alleviate poverty (Ashkin, 2019).

Biodegradable bioplastics can also help reduce permanent litter. The biodegradation of biodegradable plastics can occur within 20-45 days into CO₂ and water (H₂O) if sufficient humidity, oxygen, and an adequate number of microorganisms are present, which can be found in natural landfills or manure. In comparison, conventional plastics have a lifespan of hundreds to thousands of years (Moshood et al., 2022). Therefore, the use of biodegradable bioplastics can significantly decrease the accumulation of plastic waste in the environment and decrease the harmful effects of plastic pollution on wildlife and ecosystems. However, it's important to note that biodegradable plastics still require proper disposal and management to ensure they don't end up in the environment and contribute to pollution (Pascoe Ortiz, 2023).

However, there are also some drawbacks to consider when it comes to bioplastics, even though they offer advantages. The production of bioplastics is hindered by the higher production costs compared to traditional plastics, as they are two to three times more expensive and have lower yields. Moreover, the manufacturing process of bioplastics is plagued by various challenges. For instance, some bioplastics have inferior mechanical properties, making them more brittle and easier to rip than oil-based plastics. Additionally, bioplastics may have weaker barrier properties than conventional plastics, which can lead

to a shorter lifetime. Despite these limitations, efforts are underway to improve the production and mechanical properties of bioplastics to make them a more viable alternative to conventional plastics (Ibrahim et al., 2021). One of them is forming bioplastics from agricultural waste.

2.3.6 Application of Bioplastics in Reducing Greenhouse Gas Emissions and Promoting a Sustainable Environment

In the previous chapter, it has been mentioned that bioplastics can help reduce the carbon footprint.

2.4 Agricultural Waste

The agricultural-based industry in Malaysia has flourished due to its favourable geographical location, which includes its proximity to the equator and the fact that it is surrounded by the ocean. Furthermore, the region's climate is highly advantageous for the industry to bloom due to its classification as hot, humid, and rainy throughout the year (Fadzil & Othman, 2021). Due to this reason, agricultural exports rose significantly from RM118.7 billion in 2020 to RM154.5 billion in 2021, while total imports in the sector also increased from RM98.3 billion in 2020 to RM120.5 billion (Department of Statistics Malaysia, 2022).

Raw agricultural products specifically vegetables, fruits, poultry, crops, and dairy products that are grown and processed always produce residues called agricultural wastes. Annually, a huge number of residues are released from the agricultural-based industries that would cause pollution to the environment as well as bringing damaging effects to human and animal health if the residues are not disposed according to the correct procedure. The wastes are usually burned, dumped, or eventually end up in an unplanned landfilling, as most of the agro-industrial wastes are untreated and underutilized (Bala et

al., 2023). This is unfortunate as the wastes may contain materials that benefit human and can be found in liquid, slurries, or solids form (Jilbee, 2022). To put this into perspective, it is reported that agricultural waste production worldwide amounts to 998 million tonnes annually, with Malaysia contributing 1.2 million tonnes of waste disposed of in landfills each year. This highlights the significance of the agricultural sector in meeting human needs and supporting our livelihoods (Ali, 2020).

Agricultural waste materials like wheat straw, rice straw, and corn stalks contain a significant amount of lignocellulose, which is mainly composed of cellulose (37-43%), lignin (16-20%), hemicellulose (20-33%), and extractives (Antony & Thottiam Vasudevan, 2018). This waste shows great potential for producing high-value chemicals and phenolic compounds that can serve as substitutes for conventional petroleum-based fuels (Sivagurunathan et al., 2021). In addition to energy and chemical production, lignocellulosic waste can also be used as a feedstock to produce bioplastics. Bioplastics made from lignocellulosic waste have the potential to be biodegradable, compostable, and have lower environmental impacts compared to traditional petroleum-based plastics.

Sago, one of Malaysia's most vibrant agricultural industries, stands out as an active and thriving sector especially in Sarawak. It is said that Sarawak has been exporting around 51.27% of its total sago starch export volume to Peninsular Malaysia and 35.47% to Japan (Ling, 2022). Therefore, creating a huge amount of sago waste. Despite the potential value of its lignocellulosic content, the sago biomass is currently under-utilized, which is regrettable. In the next chapter, more information on the sago industry is discussed.

2.5 Sago

Sago (*Metroxylon sagu*) is a plant that is indigenous to Southeast Asia, and it is primarily cultivated in countries such as Malaysia, Indonesia, and Papua New Guinea. These countries are known for their extensive cultivation and production of sago, which is an important source of starch and a staple food in the region (Zhu, 2019).

2.5.1 Sago Palm

Sago palms have specific requirements for optimal growth. Sago palms require a minimum temperature of 15 °C to thrive, and if the temperature drops below 13 °C during the seedling stage, the plants are unable to survive, and the likelihood of mortality increases. Meanwhile, the optimum humidity is said to be 90% (Karim, 2021).

During the vegetative stage, the trunk is filled with nutrients that are converted into starch right before flowering. The palm dies shortly after it flowers once, therefore it is called hapaxanthic (Amin et al., 2019). Sago palm can grow a large trunk that can reach up to 10 meters with 75 cm thickness. It can produce up to 180 kg of sago starch in one trunk of sago palm (Valdez, 2022).

2.5.2 Sago Benefits

Growing sago palms has their importance which can benefit the environment, human and multiple industries.

2.5.2.1 Sago Growth Conditions

Sago palms can grow in low-lying flooded areas and upland regions due to their resilience against prolonged flooding and strong winds (Trisia et al., 2021). Moreover, provided that the pneumatophores (aerial roots that grow vertically upwards in swampy plants) are not submerged, sago palms can grow in swampy conditions. This means that the

palms can tolerate growing in areas with high moisture content, as long as their aerial roots are not completely underwater (Azhar et al., 2022). The ability of sago palms to grow in swampy conditions is due to several factors, including the high levels of organic matter and mineral nutrition in the soil, as well as the slightly acidic pH of the standing brown water that doesn't flow. These conditions are conducive to the growth of microorganisms, which can aid in sago palm cultivation. Moreover, the palm's tolerance to salinity enables it to grow in areas close to the sea that are near swamp region (Lim & Chung, 2020).

2.5.2.2 Environment

The palm parts such as sap, pith, leaf petioles, bark and “hampas” (fibrous residue) are useful raw materials for many industries, thus making the sago palm a cash crop with great economic value (Lim et al., 2019) hence reduce the amount of waste released to the environment. Moreover, there has been huge amount of carbon dioxide released to the atmosphere because of industrialization and high number of motorized vehicles. Therefore, the greenhouse effect and global warming could be mitigated because the sago forest could act as a carbon sink (Orentlicher, 2019).

2.5.2.3 Sago starch

Sago starch is a popular ingredient for industrial applications, thanks to the sago palm's ability to produce large quantities of starch. Each sago palm can produce a substantial amount of starch harvest, with approximately 150-300 kg of dry starch per plant. This high output of starch has made the sago palm a valuable resource for various industrial purposes (Achudan et al., 2020). Multiple stages are needed to extract good quality and quantity of starch that is present in the pith from cellulosic materials. The bark with common thickness of 2 to 3 cm is first removed to reach the soft tissue of the pith. Afterwards, the sago palm undergoes a maceration process using a rasper. This involves

either manual or mechanical rasping to break down the pith and release the starch particles from the fibre. Once the starch particles have been loosened from the fibrous material through the rasping process, the starch must be separated from the fibres. This is typically accomplished through one of three methods: hand kneading, trampling by feet, or spraying the mixture with water. These methods help to remove the starch from the fibrous material and isolate the pure starch particles. After the starch has been separated from the fibres, it is further processed to remove any remaining impurities. This involves passing the starch through a series of centrifugal sieves to filter out any coarse fibres. The refined starch is then extracted using cyclone separators before being dried. The drying process involves using a rotary drum dryer to remove moisture from the starch, followed by hot air drying to achieve the desired level of dryness. By the end of these processes, the sago starch is purified, refined, and ready for use in various applications (Amin et al., 2019).

Sago starch finds use in a diverse range of food products, including staple foods like papeda (a dough-like dish served with soup). The versatility of sago starch has made it a popular ingredient in many different types of cuisine (Dewayani et al., 2024). Meanwhile, in non-food industries, sago starch has huge potential in producing biodegradable plastic, paper production finishing agent, component of glue for sticking plywood sheets together as well as paper box and many more. Meanwhile, in the biotechnology industry, multiple studies were carried out to produce ethanol from sago starch (Kiddee et al., 2019).

2.5.3 Sago in Sarawak

The Sarawak government is aiming to make sago as one of the major commodities that will be contributing to the Gross Domestic Product (GDP) and is currently committed to develop the industry. The Deputy Chief minister and Minister of Modernisation of

Agriculture, Native Land and Regional Development, Datuk Amar Douglas Uggah mentioned that sago is one of the key agriculture trading commodities of Sarawak since the 1880s and the government has been involved in both upstream and downstream research activities of the crop. RM22 million has been allocated under the Sago Development Program, with the purpose of new planting and rehabilitation of sago small holdings. Therefore, 1441 hectare of new planting and 2562 hectare for rehabilitation have been implemented since 2016, that has benefited 2480 farmers. Based on Table 2.3, the total sago area in Sarawak which involves both smallholders and mini estate are 51,518 hectares, this value includes both matured and immature crops.

Table 2.3: Sago Areas (Craun Research, 2018)

	Matured (hectares)	Immature (hectares)	Total (hectares)
Small Holder	28,110	18,658	46,768
Mini Estate	1,220	3,530	4,750
Grand Total	29,330	22,188	51,518

2.5.4 Sago Starch in Sarawak

Meanwhile, sago starch is among the crucial food sources. For years, Sarawak has become the main exporter of sago starch. Data from 2018 as shown in Table 2.4 shows that the sago starch exported to Peninsular Malaysia has the highest quantity, followed by Japan and Singapore. In total, around 42,000 tons of dry sago starch has been exported with the value nearing RM90 million. After oil palm, pepper and rubber, sago became the fourth highest agricultural revenue earner for the State (Chua, 2022).

Table 2.4: Sago starch export performance by destinations in 2017 (Craun Research, 2018)

Countries	Quantity (tonne)	Value (RM)
Peninsular Malaysia	21,189,796	42,326,373
Japan	13,379,700	30,639,090
Singapore	2,798,500	6,222,099
Thailand	2,521,600	5,522,929
Vietnam	832,500	1,748,250
Myanmar	110,005	254,049
China	98,000	224,798
Indonesia	22,500	50,241

2.5.5 Sago Waste

Sago waste is often merely disposed to the environment without much effort. Fortunately, the waste can bring benefit to humans in multiple ways. Sago waste is mainly generated during the extraction of sago starch.

2.5.5.1 Sago Waste Effluent

Throughout the production process of sago starch, a considerable amount of wastewater (20 litres of effluent per kg of sago starch produced) is generated. Due to its high concentration of organic matter (e.g., protein, lipids, and carbohydrates), the effluent is known to be acidic and has an unpleasant odour, causing pollution and negatively affects the global environment quality (Rasyid et al., 2020). It is also stated by Rashid et al. (2024) that finely milled fibres, inextricable starch, and polyphenols (micronutrients from plant-based foods) are found in the sago factory effluent. The substances are discoloured and prone to putrefaction (the process of decay or rotting in a body or other organic matter). To

treat the wastewater, sedimentation ponds are commonly used, but they have been known to have harmful effects on the surrounding areas, such as producing a pungent smell (Rashid et al., 2024).

2.5.5.2 Sago Bark

Sago bark waste is a rich source of renewable lignocellulosic biomass. This waste can be classified into two types: peeled and shredded. The peeled type, which usually originates from the lower part of a sago tree, is manually peeled using a parang due to its uneven shape and typically has a thickness of 2 to 3 cm. On the other hand, shredded sago bark is produced when a machine is used to remove the bark. In Malaysia, the commercial sago starch industry produces more than 20,000 tons of sago bark waste annually, which is considered a by-product and discarded (Amin et al., 2020). To prevent accumulation, most of the sago bark is burned, which causes air pollution. In addition, sago bark waste can also be incinerated for power generation or left for natural degradation (Hamidi, Ahmed, Omar, & Chong, 2021). Around sago mills, sago barks are utilised as a flooring material (Gan et al., 2019). In order to solve the pollution issues caused by the significant amount of sago bark left in the environment, some research has been done to transform sago bark into a higher value-added product.

Due to sago bark's abundance in the sago starch processing industry, research done by Wahi et al. (2022) found that heavy metal adsorption in water can be efficiently achieved by modifying sago bark microwave biochar with acid and base to increase its porous structure and surface area, which is produced through a cost-effective and eco-friendly microwave pyrolysis process from sago bark waste. This study and others that utilizes sago bark offer promising solutions for both pollution remediation and sago bark

waste management. Table 2.5 presents the composition of sago bark, which indicates a high percentage of cellulose in its composition.

Table 2.5: Composition of sago bark (Amin et al., 2019)

Reference	(Ethaib et al., 2016)	(Erabee et al., 2017)
Cellulose (%)	40.8	44.1
Hemicellulose (%)	22.3	21.1
Lignin (%)	25.9	23.3

2.5.5.3 Sago Pith Waste

During starch extraction, a starchy lignocellulosic by-product is produced from sago palm, called sago pith waste (SPW). It is revealed through microscopic examination that a huge number of starch granules are entrapped by the lignocellulosic matrix. This can be proved by observing the composition of SPW in Table 2.6. There are many usages of SPW, including feed for animals such as swine around the sago processing areas, particleboard manufacture, mushroom culture compost and many more. However, most sago mills discard this SPW together with sago effluents the nearby area, causing water pollution. As a result, several research has been done to turn SPW into a higher value-added product to address the pollution challenges brought on by the large volume of SPW dumped into the environment.

One of its important applications is production of biogas, if the SPW is used as additional carbon in anaerobic digesters (Lim et al., 2019). An eco-friendly and low-cost adsorbent was also created from SPW and evaluated for removing methylene blue, with sago-grafted silica 80:20 exhibiting superior adsorption capacity compared to other

materials, suggesting it as a potential natural sorbent for environmental clean-up (Rajan et al., 2018).

Table 2.6: Composition of SPW (Amin et al., 2019)

Reference	Lee et al., (2014)	Jenol et al. (2014)
Starch (%)	37.0	49.5
Cellulose (%)	40.0	26.0
Hemicellulose (%)	13.0	14.5
Lignin (%)	5.0	7.5

2.5.6 Bioplastic from SPW

Several studies have explored the use of SPW in the production of bioplastic films, either as a standalone matrix or as a reinforcing filler, to enhance their mechanical properties. A study carried out by Tan et al. (2021) extract starch from SPW using ultrasound and transform it into a bioplastic film, demonstrating the potential for SPW as a sustainable and greener alternative. The tensile strength of the bioplastic film produced is however the lowest when compared to other studies as shown in Table 2.7. The absence of a reinforcing filler in the matrix may result in relatively lower mechanical properties of the bioplastic film. This study did not only extract sago starch from SPW, but also incorporated aluminium oxide (Al_2O_3) as a reinforcement filler to enhance the mechanical properties, as evidenced by the tensile test results obtained in their study (Amatullah et al., 2022).

Cellulose can be utilized to produce bioplastics. Cellulose fibres can also be extracted from SPW, based on the research done by Yacob et al. (2018) This study aimed to improve the low mechanical properties of sago starch-based films by adding cellulose

fibres extracted from sago waste, which helped improve the mechanical properties. The study shows promising results for tensile tests.

Table 2.7: SPW-based Bioplastics

Study	SPW Preparation	Bioplastic Film Preparation	Mechanical Properties
(Tan et al., 2021)	Extraction of starch from SPW	Solution casting of extracted starch	TS: 0.9 ± 0.1 MPa E: $13.6 \pm 2.0\%$
(Amatullah et al., 2022)	Extraction of starch from SPW	Solution casting of extracted starch with aluminium oxide (Al_2O_3) as filler	TS: 3.41 MPa E: 38.66%
(Yacob et al., 2018)	Cellulose fibres extracted from SPW	Solution casting of sago starch as matrix and extracted cellulose as filler	TS: 38.66 MPa to 40.70 MPa E: 3.85% to 4.62%

2.6 Trifluoroacetic Acid (TFA)

Trifluoroacetic acid (TFA), with chemical formula of $\text{CF}_3\text{CO}_2\text{H}$ is an organofluorine compound, which is an organic compound that contains a carbon-fluorine bond. The chemical compound of TFA closely resembles acetic acid as both have similar basic structure. The notable difference is that all three atoms in the acetyl group of acetic acid are replaced by fluorine atoms. This substitution is what makes TFA unique. Moreover, this compound is a colourless liquid that smells like vinegar (EMBL-EBI, 2019). TFA is also a strong organic acid with pK_a of approximately 0.43 and is highly soluble in water (Dekant & Dekant, 2023).

2.6.1 TFA as Common Solvent for Bioplastic Film Production

TFA is used as a solvent in chemical reactions to solubilize cellulose in a non-aqueous system. Throughout this reaction, TFA acetylates itself to the hydroxyl groups of

the cellulose molecules. This results in the production of cellulose derivatives, where the hydroxyl groups have been modified by the attachment of trifluoroacetyl groups. Cellulose derivative has different chemical properties compared to the original cellulose. Nonetheless, cellulose derivative that was formed by the reaction with TFA is not very stable as the derivative can readily undergo hydrolysis when exposed to water vapour or even moisture in the air. As a result, the cellulose derivative hydrolyses and reverts to its original form as cellulose, forming an amorphous and free-standing cellulose film (Guzman-Puyol et al., 2019). TFA can also solubilize cellulose with other organic matter such as hemicellulose. It is also mentioned that TFA can partially dissolve lignin (Bayer et al., 2014).

Trifluoroacetic acid is an organic acid that occurs naturally in the environment and can be broken down by microbial activity. In addition, due to its high volatility, TFA is recyclable by distillation (Tedeschi et al., 2020).

MCC and plant wastes, as well as combinations of cellulose with seaweeds, silk, nylon, and poly(vinyl alcohol), have recently been utilised to create bioplastic films using TFA. However, there are no studies that uses cellulose fibres extracted from SPW that uses TFA for bioplastic film production. Thus, the research will focus on extracting cellulose from SPW and digesting the CF in TFA to form a bioplastic film with good properties.

2.7 Chapter Summary

In this literature review, several aspects related to the research were discussed. The topics include synthetic polymers and their impact to the environment as well as presenting one of their alternatives, bioplastics. The classification, types, characterization, advantages, and disadvantages of bioplastics were discussed. Based on past research, the development of bioplastics had utilised agricultural waste such as SPW as one of their raw materials. In

addition, the chapter also explored the methods of cellulose extraction from SPW and the utilisation of TFA as a solvent to produce bioplastic. Therefore, the literature review provided a strong starting point for the research to develop a bioplastic film from SPW.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Materials

The materials and chemicals used in this research was sago pith waste (SPW) or sago *hampas* that was collected from Kampung Skibang, Bau after extracting starch from a sago palm. Sodium hydroxide (NaOH) (AR grade, $\geq 97\%$) was obtained from Fisher Chemical, sodium chlorite (NaClO_2) (technical grade, 80%) was obtained from Sigma-Aldrich, acetic acid (glacial, 99%) was obtained from Sigma-Aldrich and trifluoroacetic acid (TFA) (Reagent Plus, 99%) was also obtained from Sigma-Aldrich.

3.2 Methodology

The methodology of in this study include preparation of source material, extraction of cellulose and production of bioplastic films. Figure 3.1 shows the process flow diagram of the project.

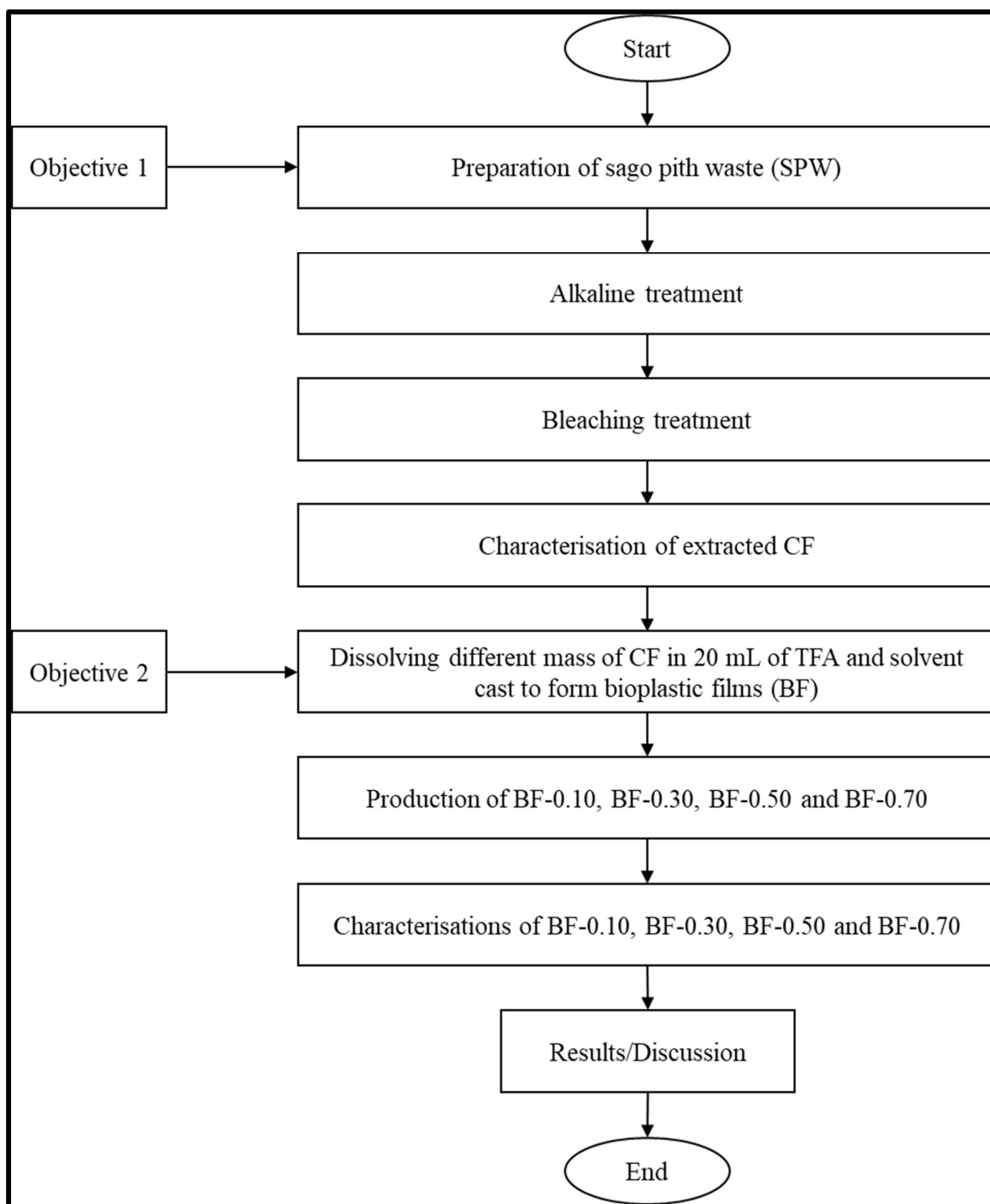


Figure 3.1: Research Flow Diagram

3.2.1 Preparation of Source Material

A sustainable raw material was decided based on many factors such as renewable resources, no competition with food supply, can help minimize waste and environmental impact, and cost-effective option. Therefore, sago pith waste (SPW), as shown in Figure 3.2, was the preferred material that was used to develop a bioplastic film. SPW was collected from Kampung Skibang, Bau after extracting starch from a sago palm. Fresh SPW were washed to remove dirt and impurities. Then, the cleaned SPW was soaked in a 40°C distilled water to get rid of excess starch (Yacob et al., 2018) and was dried in an oven. After drying, SPW was grounded into fine powder using analytical grinder at the speed of 3 for 5 minutes and sieved through a screen as shown in Figure 3.3. The fine powder expanded the amount of surface area that the alkali and bleaching solutions could access during CF extraction (K. Liang et al., 2022).



Figure 3.2: Fresh SPW Collected from Kampung Skibang



Figure 3.3: Dried SPW

3.2.2 Extraction of Cellulose

The extraction of cellulose from SPW was carried out based on methods used in previous works (Yacob et al., 2018; Jampi et al., 2021) with slight modifications to optimize each step. The SPW was treated with 4% w/v NaOH and bleached with NaClO₂ and acetic acid solution.

3.2.2.1 Alkaline Treatment

10 g of SPW was weighed and dried in an oven overnight to remove excess moisture. Then, the 500 mL of 4% NaOH was poured into a beaker and placed on top of a hot plate with the temperature maintained at 70°C as shown in Figure 3.4. Then, the SPW was immersed into the beaker and the solution was stirred by using a magnetic stirrer. This process was done for one hour. Then the solution was filtered to obtain the remaining solute by using a Buchner flask, Buchner funnel, filter paper and vacuum pump as shown in Figure 3.5. This process was repeated three times to ensure effectiveness.



Figure 3.4: Powdered SPW in 4% w/v NaOH Solution



Figure 3.5: Buchner Funnel, Buchner Flask, and Vacuum Used for Filtering Process

3.2.2.2 Bleaching Treatment

The remaining solute underwent bleaching with a solution containing 160 mL of distilled water, 1 mL of glacial acetic acid and 1.5 g of sodium chlorite (Pushpamalar et al.,

2006). This process was done by using a screw-top Erlenmeyer flask that was placed inside a water bath that was maintained at 70°C for 3 hours, as shown in Figure 3.6 (Pushpamalar et al., 2006). This process was repeated three times to ensure effectiveness. When the bleaching process was done, the solution was filtered with a Buchner flask, Buchner funnel, filter paper and a vacuum pump as shown in Figure 3.5. After filtering, CF was obtained and cleaned thoroughly with distilled water until the pH of solvent obtained in Buchner flask was neutral (Yacob et al., 2018). The CF was then dried in the oven at 40°C overnight. The product yield of the treatment of SPW was calculated using Equation 3.1 (Pinto et al., 2022).

$$\text{Product yield, } y_p = \frac{\text{Mass of product (g)}}{\text{Mass of SPW}} \times 100 \quad \text{Equation 3.1}$$



Figure 3.6: Bleaching Process

3.2.2.3 Cellulose Extraction from SPW

Observationally, bleached cellulose fibres extracted from SPW changed colour to white, clearly showing that most of the original non-cellulosic components had been removed as seen in Figure 3.7.

It was also observed that a minor portion of the cellulose was brownish, which was due to the residual non-cellulosic component that were undissolved during both treatments. This finding aligned with existing research which indicated that as the undissolved non-cellulosic content in the cellulose fibre increased, there was a corresponding decrease in their brightness or whiteness level (Arnata et al., 2019). Similar studies had proven that the treatments did not completely remove the non-cellulosic components of the raw materials. After the alkaline and bleaching of sago frond to extract cellulose, the non-cellulosic component of sago frond was not completely removed as the whiteness of cellulose sago frond was 79.13% and had relatively low content of lignin and hemicellulose (Arnata et al., 2019). Another study also had extracted cellulose from pineapple leaf fibre through alkali and bleaching treatment (Fareez et al., 2018). They also found that the residual lignin in the cellulose fibres was around 0.4% to 2.8%. Therefore, this past research confirmed that the treatments did not completely remove the non-cellulosic component of the SPW, and these components were still present in the cellulose fibres obtained.

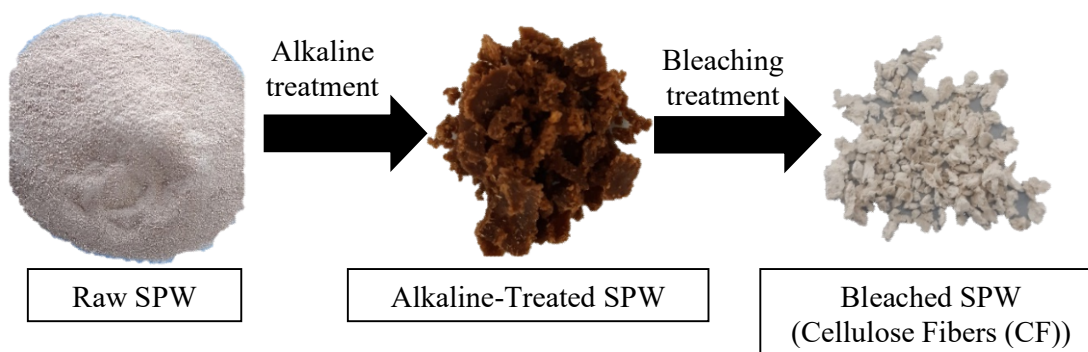


Figure 3.7: Extraction of Cellulose from SPW

3.2.3 Production of Bioplastic Films

To avoid any moisture, the CF was dried again by placing it in a 40°C oven overnight. The next day, 0.10 g of CF was weighed with A&D Weighing Scale and placed in a reagent bottle containing 20 mL of trifluoroacetic. 20 mL of TFA was used as past research also used 20 mL of TFA to solubilize their raw materials and formed bioplastic films (Bayer et al., 2014). The reagent bottle was placed in a water bath that was maintained at 50°C on a hot plate. The solubilisation was done at 50°C temperature so that the solubilisation process would be accelerated (Bayer et al., 2019). All the mixture was then stirred with a magnetic stirrer for three days in order to ensure effective solubilisation of CF, similar to what was done by Bayer et al. (2014). The mixture was then centrifuged by using Kubota Programmable Universal Centrifuge to separate the impurities and undissolved component of CF such as silica bodies (Bayer et al., 2014). The procedure was repeated with different weight of CF, which are 0.30 g, 0.50 g, and 0.70 g. The solution was cast in a Petri dish to obtain free-standing bioplastic films and placed in a fume hood to let the solvent evaporate overnight. The films were labelled as BF-0.10, BF-0.30, BF-0.50 and BF-0.70 in which BF stands for bioplastic film and the numbers refer to the amount of CF solubilized in 20 mL of TFA as shown in Table 3.1. These masses were

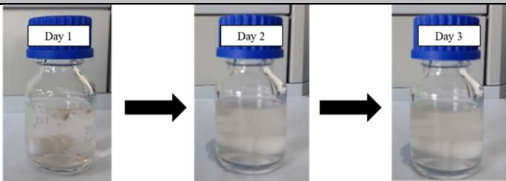
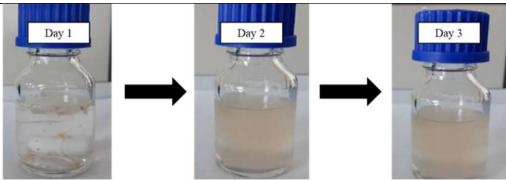
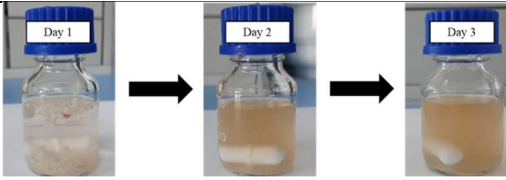
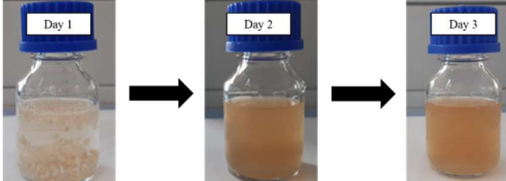
chosen based on the recommendation by Bayer and team, which states that the starting material should typically start with 0.5% by weight in TFA solution, which is around 0.1 g in 20 ml TFA. They also stated that the preferred amount of starting material is from 1% to 2% by weight, which is around 0.3 g to 0.6 g of starting material in 20 ml of TFA (Guzman-Puyol et al., 2022).

Table 3.1: Bioplastic Films Label

Mass of CF in 20 mL of TFA	Label
0.10 g	BF-0.10
0.30 g	BF-0.30
0.50 g	BF-0.50
0.70 g	BF-0.70

To standardise the bioplastic films forming process, the solubilisation process of all CF in 20 mL of TFA was done 3 days to ensure effective solubilisation of CF (Bayer et al., 2019). After 3 days, the bioplastic films were cast in Petri dishes. The formulation has successfully produced free-standing bioplastic films as shown in Figure 3.8. Based on Table 3.2, it was observed that the lower the mass of CF immersed in the TFA, the faster the solubilisation process. The smaller amount of cellulose meant that there was smaller amount of cellulose polymer chains to be disintegrated (Sirviö, 2019).

Table 3.2: Observation Recorded from Day 1 to Day 3 of the Solubilisation of CF

Mass of CF (g)	Observation recorded from Day 1 to Day 3 of the solubilisation of CF	Time taken to solubilise
0.10		6 hours
0.30		12 hours
0.50		26 hours
0.70		32 hours

After the solvent was completely evaporated, the bioplastic films produced were transparent as shown in Figure 3.8 but exhibited a distinct brown coloration, with BF-0.70 being the most intense. This was due to the increasing amount of brownish portion of the cellulose, which was the residual non-cellulosic component present in the CF, as the amount of CF dissolved in 20 mL of TFA was increased. This was proven again by similar research which stated that the bioplastic films produced exhibited brown coloration due to the presence of a high number of organic compounds in the matrix (Bilo et al., 2018). In

context, instead of cellulose, TFA can partially break down lignin and hemicellulose as well as other non-cellulosic polysaccharides (Bayer et al., 2014; Tedeschi et al., 2020).

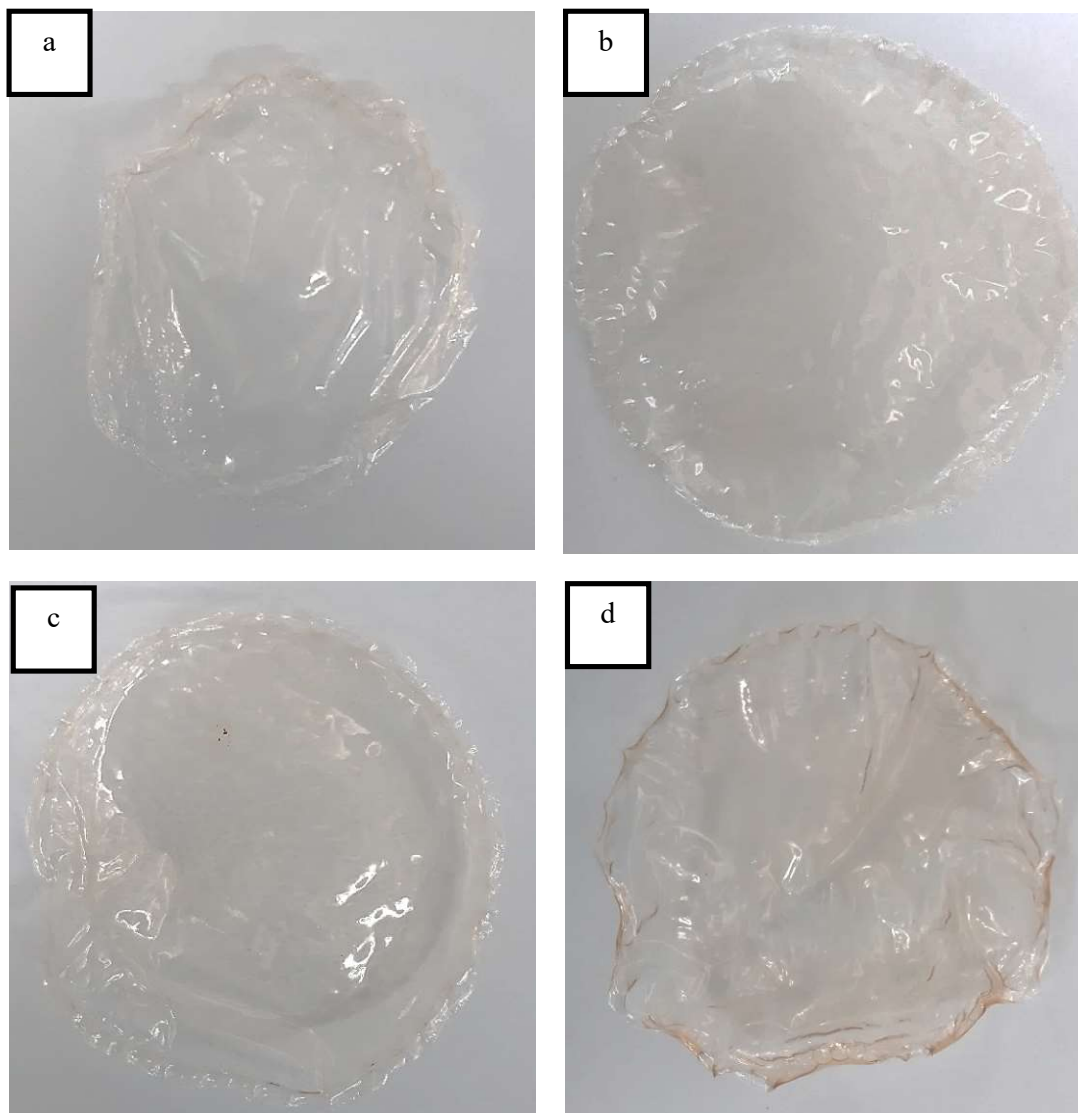


Figure 3.8: a) BF-0.10, b) BF-0.30, c) BF-0.50 and d) BF-0.70

3.2.4 Overview of the Overall Process

The summary of the methods taken to form a bioplastic film from SPW was represented in Figure 3.9.

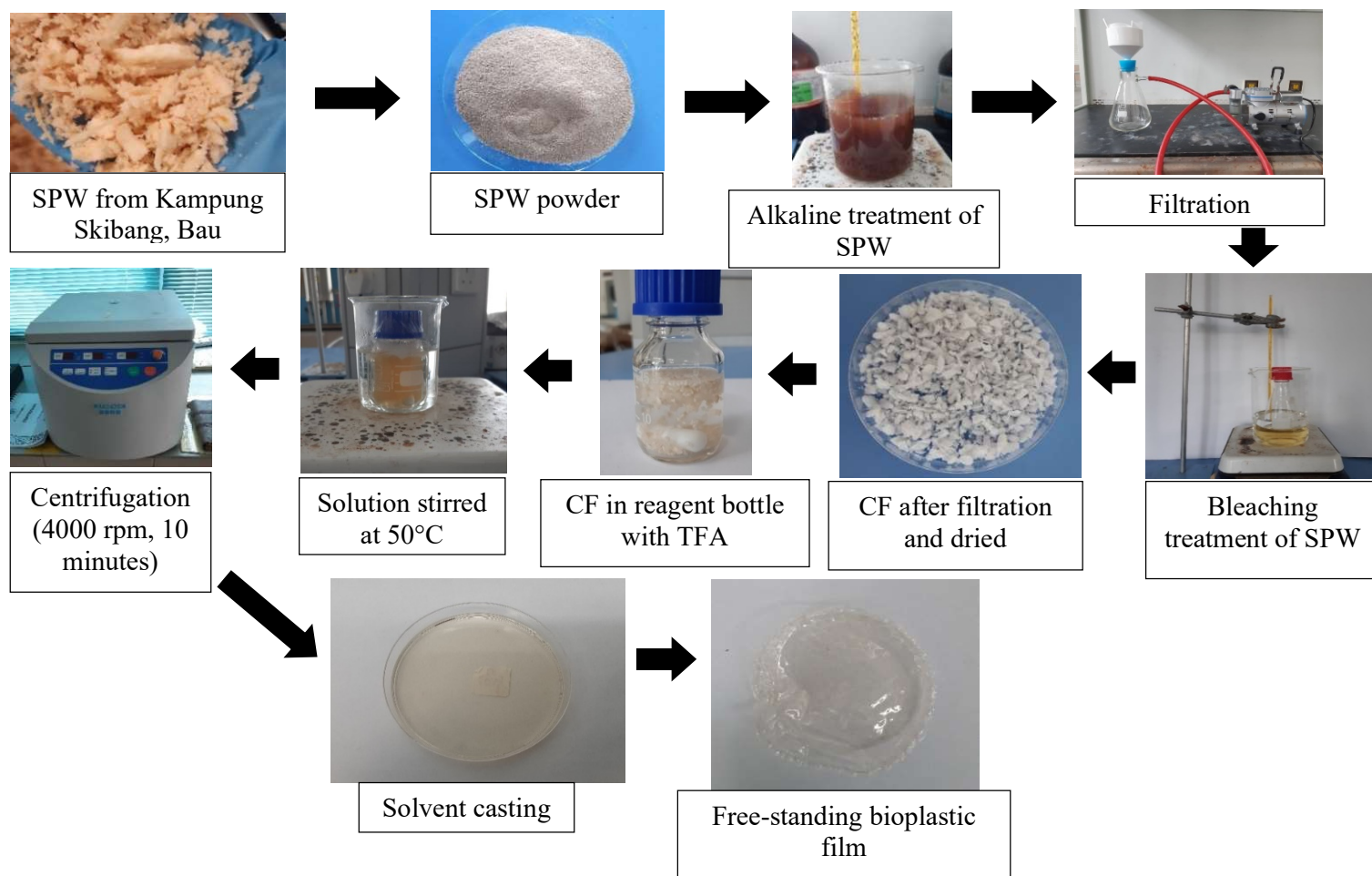


Figure 3.9: Schematic Representation of the Process of Cellulose Extraction and Bioplastic Film Formation

3.3 Characterisations of Bioplastic Films

The bioplastic films had undergone Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), tensile test, thermogravimetric analysis (TGA) and water absorption.

3.3.1 Fourier Transform Infrared Spectroscopy (FTIR) Analysis

Fourier transform infrared attenuated total reflectance spectroscopy (FTIR-ATR) was carried out to identify functional groups and identify any potential chemical alterations in the SPW after treatment and the bioplastic film samples formed. The spectra were analysed on Shimadzu IRAffinity-1 in the 4000-600 cm^{-1} regions with a resolution of 1 cm^{-1} .

3.3.2 Morphological Properties Analysis

Scanning electron microscope (SEM) images of the SPW, CF, and all the bioplastic films produced were taken by using SEM (Hitachi TM4000Plus Tabletop Microscope, Tokyo, Japan). The images were taken from the surface of the samples and were collected at magnification of $\times 500$ and $\times 1000$ with energy of the beam at 15kV. Energy dispersive X-ray analysis (EDX) was also carried out during SEM imaging to investigate the elements present in the samples.

3.3.3 Mechanical Properties Analysis

For tensile strength and Young's modulus evaluation, a tensile test was carried out by using universal testing instruments (Shimadzu Autograph AGS-S50kNX, Japan). The crosshead speed was 0.5 mm/min, with sample's testing length and width to be 40 mm and 5 mm respectively. Equation 3.1 was used to calculate the tensile strength of the bioplastic films:

$$TS \left(\frac{N}{mm^2} \right) = \frac{\text{maximum force to rupture}}{\text{area of sample}} = \frac{F_{max}}{A} \quad \text{Equation 3.1}$$

F_{max} (N) is the maximum force needed to break the bioplastic film during the tensile test, meanwhile A (mm^2) is the sample's area, which can be calculated by multiplying the sample's width and length. To find the Young's modulus, a stress strain graph was plotted in Microsoft Excel from the data obtained, and the slope, m from the Equation 3.2 below, of the linear region of the stress strain curve was determined.

$$y = mx + c \quad \text{Equation 3.2}$$

3.3.4 Thermal Properties Analysis

Thermogravimetric analysis was carried out to establish thermal stability of bioplastic by using TG Analyzer Spectrum 500 and analysed by the Universal Analysis 2000 between 30°C and 600°C with a heating rate of 10°C/min. TGA curve were obtained from the analysis.

3.3.5 Water Absorption Test

A bioplastic film sample with a known weight that had already been dried for 24 hours at 65°C was submerged in water for 24 hours in a 100 mL beaker of distilled water. After the experimental time, the sample was removed from the water, patted dry with a lint free cloth, and then weighed. The percentage of water absorbed was calculated by using Equation 3.3 where w_0 is the initial weight and w_1 is the final weight of the sample.

$$\text{Water absorbed} = \frac{w_1 - w_0}{w_0} \times 100 \quad \text{Equation 3.3}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1.1 Results and Discussion

To evaluate the properties of the produced bioplastic films, analyses were conducted on their FTIR spectra, morphology, mechanical strength, thermal properties, and water absorption. In addition, the bioplastic film BF-0.70 was compared with sago-based bioplastics from prior studies to identify its strengths and weaknesses and to assess its overall performance.

4.1.2 Fourier Transform Infrared Spectroscopy (FTIR) Analysis

4.1.2.1 Fourier Transform Infrared Spectroscopy (FTIR) Analysis of SPW and CF

The removal of non-cellulosic components after the treatment was evidenced by FTIR spectra of SPW and CF as illustrated in Figure 4.1.

The peaks at 1037 cm^{-1} corresponds to C-O stretching that is commonly found in cellulose, hemicellulose, and lignin (Jampi et al., 2021). The presence of peaks between 1344 cm^{-1} , 1453 cm^{-1} and 1523 cm^{-1} in SPW showed the presence of lignin for SPW. The peak at 1344 cm^{-1} was associated to aromatic C-O stretching of syringyl units present in lignin (Shi et al., 2019). Meanwhile, the peaks at 1453 cm^{-1} and 1523 cm^{-1} in SPW correspond to aromatic skeletal vibrations (C-C) of benzene rings that can also be found in lignin (Cao et al., 2021). Meanwhile, the peak around 1711 cm^{-1} was attributed to the C=O vibration, corresponding to the acetyl and uronic ester groups in hemicellulose. It was observed that the intensity of these peaks decreased which indicated that some of the non-cellulosic component might still be present in the cellulose fibres. A similar treatment done

on SPW by Yacob et al. (2024) mentioned that alkali and bleaching treatments help removes the non-cellulosic components by breaking the α - and β - aryl ether bonds between lignin and hemicellulose.

The wide broad peak in the 3500 cm^{-1} to 3000 cm^{-1} regions for both spectra was due to the presence of hydroxyl (O-H) functional group that can be found in cellulose (Md Salim et al., 2021). It was observed that the peak intensity was reduced, most probably due to the alkali and bleaching treatment on the SPW to obtain CF which cause the degradation of the intermolecular and intramolecular hydrogen bonds that most of the hydroxyl groups formed which also results in lower moisture absorption (Abu-Thabit et al., 2020).

The EDX findings in Chapter 4.1.3.1 of decreased carbon and increased oxygen composition are directly supported by these FTIR observations.

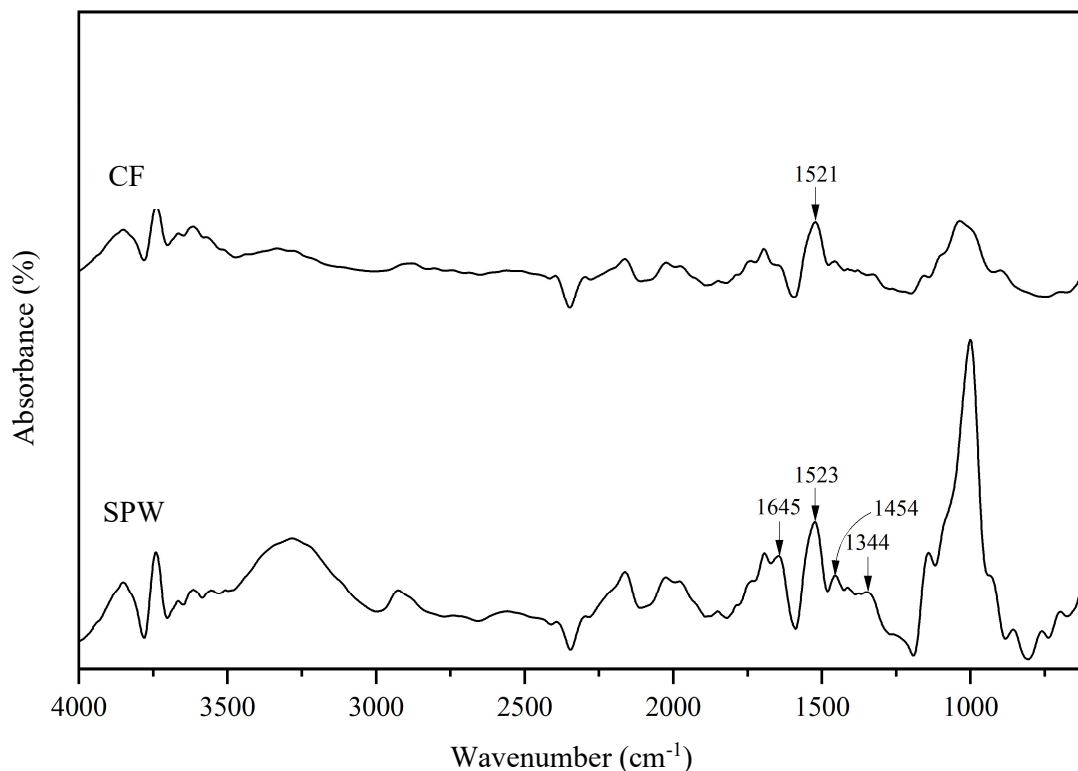


Figure 4.1: FTIR spectra for SPW and CF

4.1.2.2 Fourier Transform Infrared Spectroscopy (FTIR) Analysis of Bioplastic Films

Figure 4.2 showed the FTIR spectra for BF-0.10, BF-0.30, BF-0.50, BF-0.70 and CF. By observing the spectra, it was apparent that all four bioplastic film spectra exhibit negligible differences in their respective spectral profiles as compared to the CF spectrum. Since these functional groups are fundamental to the cellulose molecule and remain unchanged across different ratios, the spectra look identical as proven by a study by Guzman-Puyol et al. (2022), which found that despite varying cellulose content in each sample, the FTIR peaks related to cellulose showed no notable variations in peak patterns. This is because TFA only solubilizes the cellulose and other main compounds to form homogenous solution that can be cast into a bioplastic film (Bilo et al., 2018). This is further proven by the EDX analysis carried out in Chapter 4.1.3.2. The typical peaks of

cellulose exhibited by the FTIR spectra include the small broad peak observed at around 2890 cm^{-1} , that was attributed to the stretching vibration of C-H, (Tabaght et al., 2023) and a wide broad peak in the 3500 cm^{-1} to 3000 cm^{-1} regions due to the presence of hydroxyl (O-H) functional group that can be found in cellulose (Md Salim et al., 2021).

The peaks at 1015 cm^{-1} to 1037 cm^{-1} corresponds to C-O stretching that is commonly found in cellulose, hemicellulose, and lignin (Jampi et al., 2021). It is observed that the peak of 1037 cm^{-1} in CF shifted to 1015 cm^{-1} in the bioplastic films spectra, indicating a decrease in the crystallinity (Lai et al., 2013). The TFA disrupts the intermolecular hydrogen bonds within the cellulose structure. This disruption causes the cellulose molecules to rearrange, adopting a less ordered state (Bayer et al., 2019)

The appearance of a peak at 1520 cm^{-1} in all concentrations of bioplastic films was attributed to the aromatic skeletal vibration (C-C stretching), indicating the presence of lignin in the samples (Hospodarova et al., 2018) that was discussed in Chapter 4.1.2.1 and was solubilised in TFA to form a bioplastic film. TFA can partially solubilize lignin as mentioned by Bayer et al. (2014) and can be dispersed in the Bioplastic matrix in its new form.

According to a study of cellulose bonding with TFA done by Monika (2018), a peak around 1790 cm^{-1} appeared in the cellulose-TFA sample, which was attributed to the carbonyl group (C=O) of the cellulose trifluoroacetate. For this study, there were no changes in 1790 cm^{-1} peak which indicated that there was no trifluoro-acetylated residue in the films. The TFA was evaporated during the casting process in order to form a free-standing bioplastic film (Bayer et al., 2019).

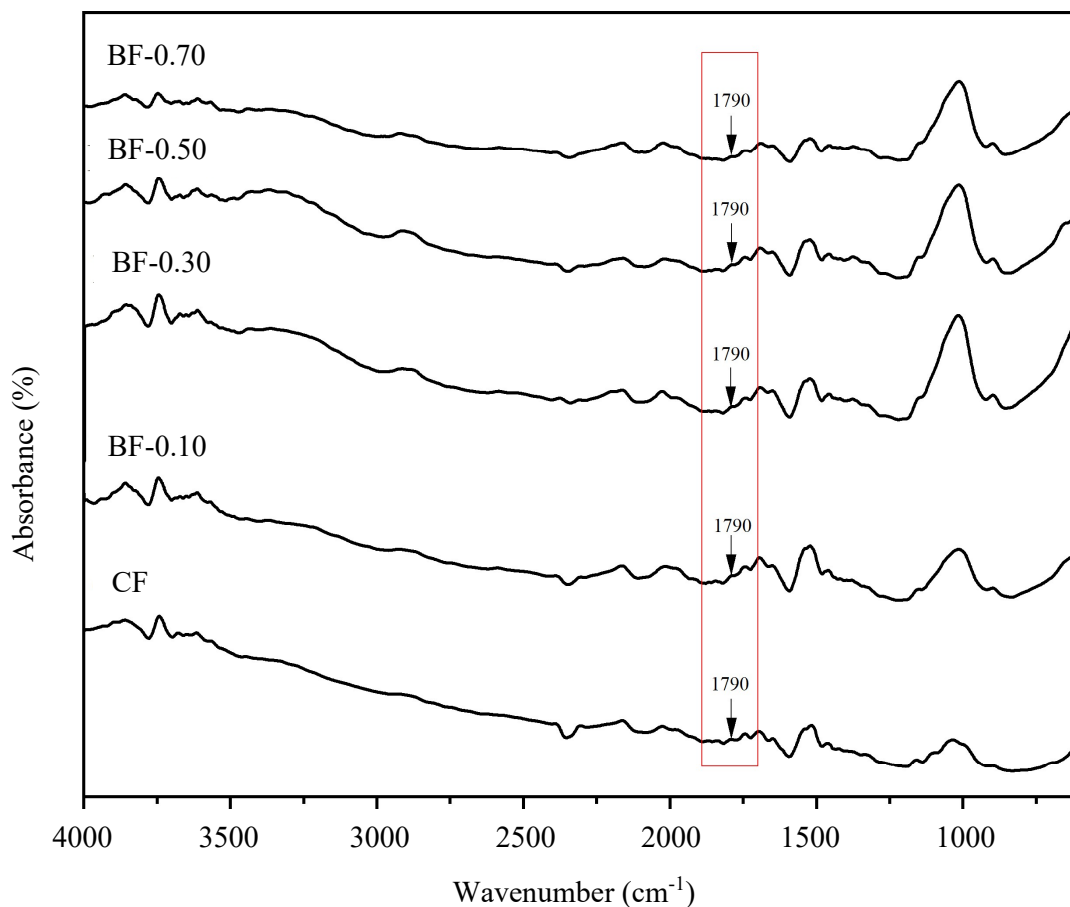


Figure 4.2: FTIR Spectra of CF, BF-0.10, BF-0.30, BF-0.50 and BF-0.70

In addition, the FTIR analysis of BF-0.70 was compared with a bioplastic film made from sago starch filled with cellulose microfibrils (SSCMF) from water hyacinth (Syafri et al., 2019).

Upon comparing the major peaks present in FTIR analysis of both bioplastic films, it was found that the two had similarities in terms of functional groups present in the bioplastic films. It was observed that the peak that only BF-0.70 had was the peak at 1520 cm^{-1} which indicated the presence of lignin in the bioplastic film. The prepared samples' bioplastic nature was confirmed by all the observed bands (Srinivasa Rao et al., 2022).

Both bioplastic films exhibited C-O stretching at peak 1011 – 1037 cm^{-1} , 1645 – 1647 cm^{-1} and around 2900 cm^{-1} in their respective spectra as shown in Table 4.1. The FTIR analysis results also demonstrated the presence of hydroxyl groups (O-H) as shared functional groups in both BF-0.70 and the SSCMF bioplastic film. In the context of SSCMF bioplastic film, this occurrence can be ascribed to the development of intermolecular associations that engage the O-H groups within the starch-cellulose microfibrils molecules (Santana et al., 2018). For BF-0.70, the presence of hydroxyl (O-H) functional group can be found in CF.

Table 4.1: Major Peaks in FTIR Spectra of Sago Starch with Cellulose Microfibrils Bioplastic Film (Syafri et al., 2019) and BF-0.70

Peak (cm^{-1})	Assignment	SSCMF	BF-0.70
1011 – 1037	C-O stretching	✓	✓
1520	C-C stretching	✓	
1645 – 1647	O-H bending of the absorbed water	✓	✓
2900	C-H symmetrical stretching	✓	✓
3000 – 3500	O-H stretching	✓	✓

4.1.3 Morphological Properties Analysis and Energy Dispersive X-ray Spectroscopy (EDX) Analysis

4.1.3.1 Morphological Properties Analysis and Energy Dispersive X-ray Spectroscopy (EDX) Analysis of SPW and CF

Morphological analysis was carried out on SPW and CF to investigate the structural properties and physical characteristics of the sample. SEM images taken from the surface of the SPW and after its treatment (CF) showed differences in their morphology. A huge amount of starch granules can be found in the SPW, which was the solid waste obtained after starch extraction. As shown in Figure 4.3a, the sago starch granule appeared to be in pear or cigar shape, along with having a smooth outer surface. After the SPW was treated, the starch granules were removed from the sample as shown in Figure 4.3b, as the pear or cigar shape particles cannot be seen in the SEM image. This was due to the alkaline treatment, as the NaOH destroyed the intermolecular and intramolecular hydrogen bonds of the starch and form multiple hydrogen bonds with H₂O molecules, which caused the starch to become more soluble (Yang et al., 2021). Furthermore, the treatment was done three times, which ensured thorough penetration of NaOH in the SPW and complete degradation of the starch.

There were also irregular sago pith fibres as can be seen in Figure 4.3a that were in multiple shapes or sizes in the SPW. These fibres consist of hemicellulose, cellulose, and lignin as the three major components (Muslimin et al., 2019). In Figure 4.3b, the morphological analysis revealed that the CF were in large bundle of fibres. The fibres were highly intertwined. This showed that the cellulose formed linkages with the residual non-cellulosic components which acted as a binder in the CF after the treatments (Asif et al., 2022) as per mentioned in Chapter 4.1.2.1. The FTIR spectra had also indicated that some

of the non-cellulosic components might still be present in the cellulose fibres after the treatment.

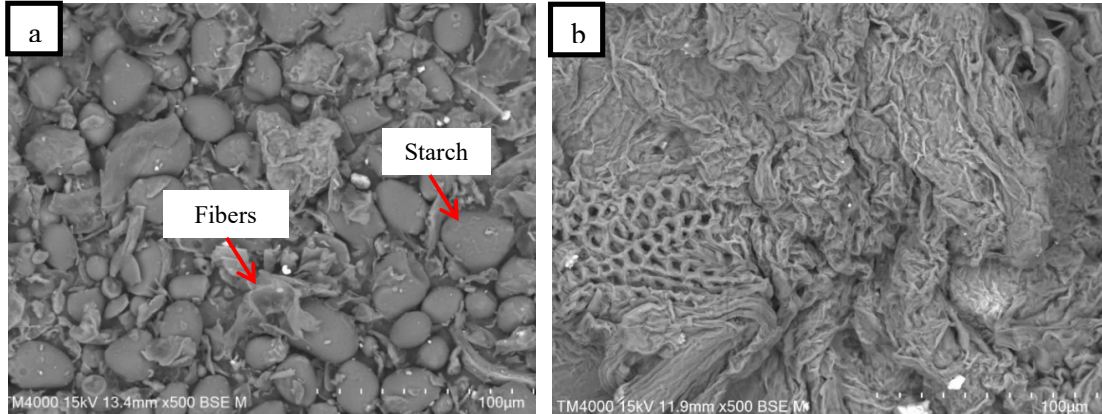


Figure 4.3: SEM Images of a) SPW and b) CF at Magnification of 500×

Table 4.2 shows the results of EDX analysis on the SPW and CF samples. The EDX analysis, which revealed a decrease in carbon composition and an increase in oxygen composition after the treatments as seen in Table 4.2, aligns with the previous FTIR findings. The treatments break down non-cellulosic components like hemicellulose and lignin, reducing the carbon content (Yacob et al., 2024). At the same time, these treatments oxidize the material, increasing the relative oxygen content by forming new oxygen-containing groups such as hydroxyl (O-H) groups which can be observed in the FTIR spectra.

Meanwhile, after treatment, only traces of nitrogen elements were still detected through EDX analysis, since the presence of nitrogen was previously indicated in the SPW sample, along with approximately 0.50 % calcium and 0.4 % potassium, consistent with findings from a study on SPW conducted by Habi et al. (2014). The analysis also revealed that there are 0.4% aluminium element in the SPW sample, which is common in biomass as it is abundant in most soil (Negreanu-Pirjol et al., 2019) and this element was still

present after the treatment of the SPW. The low percentage of sodium in CF is attributed to the alkaline and bleaching treatment during the extraction of cellulose (Chai et al., 2021).

Table 4.2: EDX Analysis of SPW and CF

	SPW			CF		
Region	1	2	3	1	2	3
	Elemental composition (%)					
Oxygen	42.30	39.52	42.30	47.89	47.30	46.14
Carbon	54.67	59.98	56.78	50.53	51.50	51.89
Nitrogen	2.63	-	-	-	1.96	1.97
Potassium	-	-	0.39	-	-	-
Calcium	-	0.50	0.53	-	-	-
Aluminium	0.40	-	-	1.21	0.89	-
Sodium				0.37	-	-

Based on the findings, the alkaline treatment and bleaching treatment for the extraction of cellulose had left some non-cellulosic component in the sample, based on the observation of SEM images, which coincided with the FTIR results of the CF.

4.1.3.2 Morphological Properties Analysis and Energy Dispersive X-ray Spectroscopy (EDX) Analysis of Bioplastic Films

Figure 4.4 below shows the SEM images of BF-0.10, BF-0.30, BF-0.50 and BF-0.70 at 500×. All the bioplastic films exhibited a smooth texture with few distinct agglomerations, indicating the undissolved component of the CF that could not be centrifuged in all the bioplastic films (Bayer et al., 2014).

However, for BF-0.10, it was observed that the surface of the bioplastic film was smooth with a bubble-like texture, which appears small, rounded and irregularly shaped features.

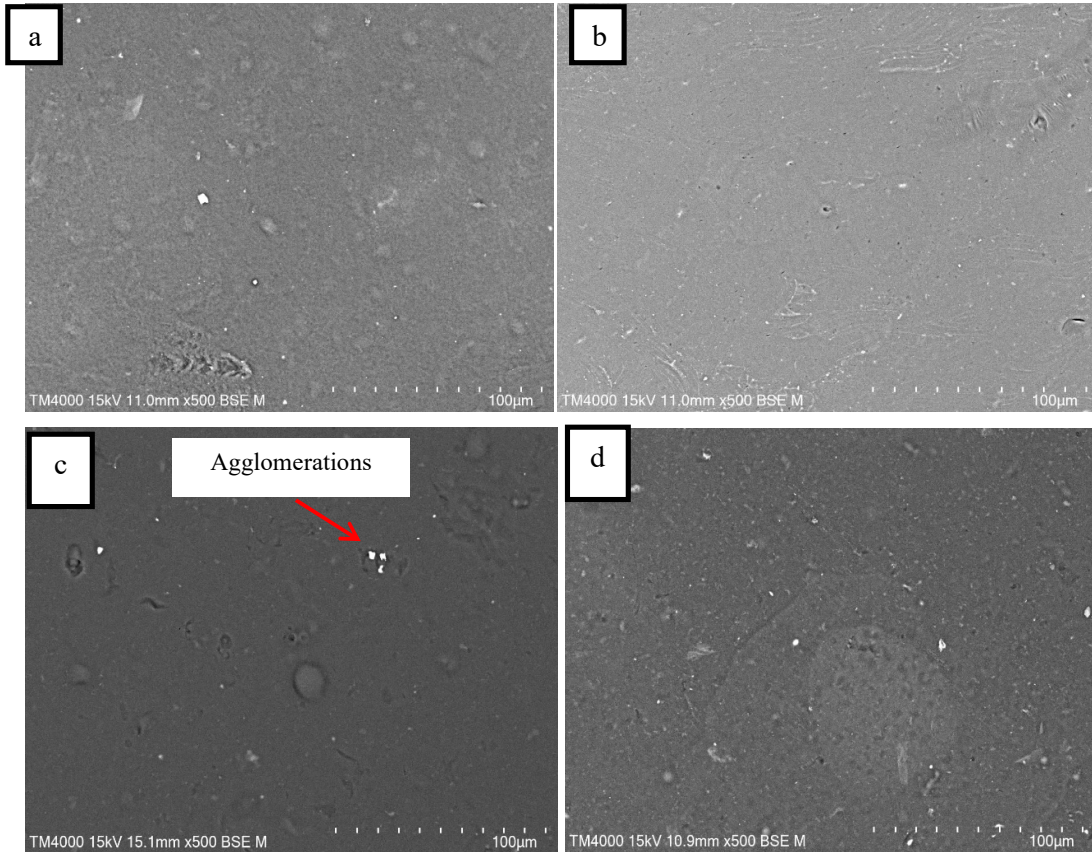


Figure 4.4: SEM Images for a) BF-0.10, b) BF-0.30, c) BF-0.50 and BF-0.70 at 500× Magnification

Figure 4.5 below shows the SEM images of BF-0.10, BF-0.30, BF-0.50 and BF-0.70 at 1000×. At higher magnification, it was observed that the texture of the surface had bubble-shape protrusions on the surface. As the mass of CF solubilized in TFA got higher, the bubble-shape texture appeared to decrease in size, and slight reduction in the number of visible pores were observed. This was most due to the more adequate distribution of the CF within the matrix as the mass increased (Gurram et al., 2018), especially for BF-0.70 as the

bubble-shape protrusions was the smallest among all the bioplastic films and had a smooth surface.

The more adequate distribution leads to a more homogeneous structure, reducing the size of surface irregularities and enhancing the overall smoothness of the film. They also serve as a starting point for a more thorough investigation of how these morphological variations had impacted the mechanical and other performance characteristics of the bioplastic films.

The relationship between the surface characteristics that were observed and the mechanical properties of the bioplastic films is noteworthy. The decrease in bubble-shape protrusions and the appearance of the smoother surface of BF-0.70 had suggested a uniform distribution of CF, which was likely to affect the tensile strength and other properties. These SEM data had offered a visual representation of the structural changes caused by the different masses of CF, as will be discussed in more detail in later chapters.

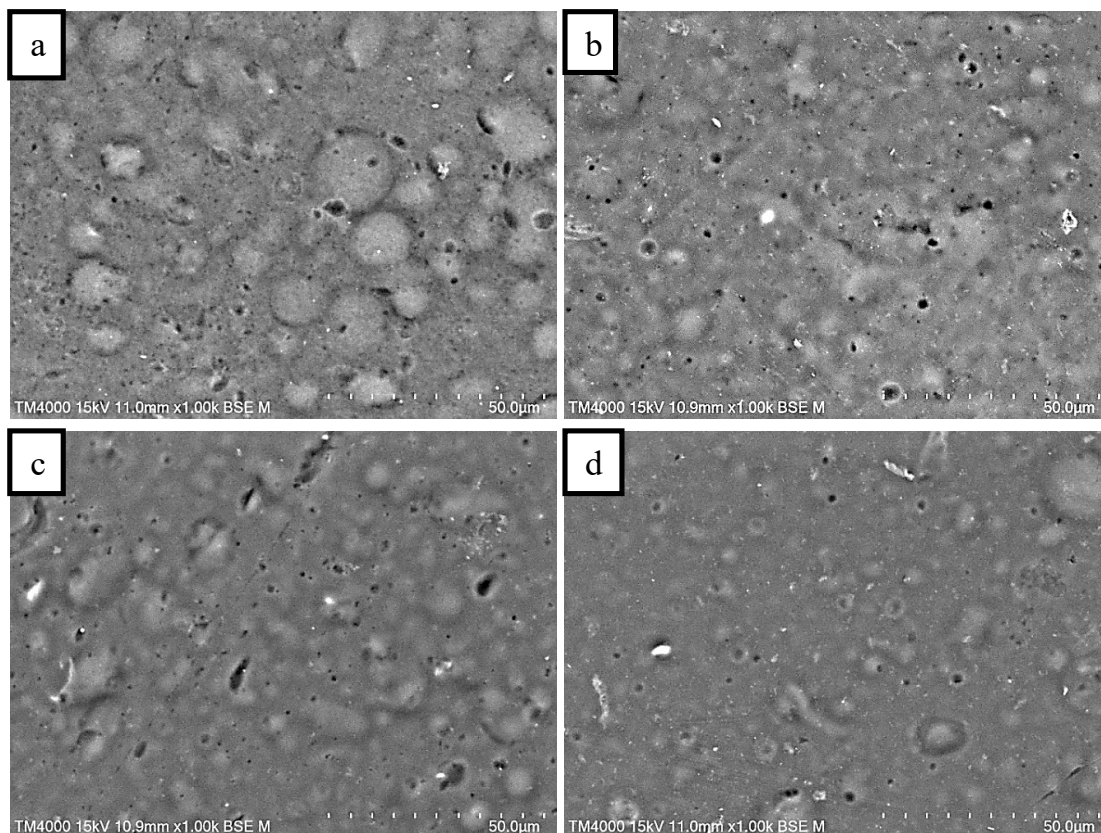


Figure 4.5: SEM Images for a) BF-0.10, b) BF-0.30, c) BF-0.50 and BF-0.70 at 1000×

In addition, the comparison with the bioplastic film by Syafrı et al. (2019) gave visual understanding of how the surface of BF-0.70 compared with bioplastic made from SSCMF, highlighting any special characteristics or differences.

The SEM image of SSCMF (Syafrı et al., 2019) had exhibited a similar surface with presence of agglomerations of cellulose microfıbres and pores. Agglomerations of the cellulose microfıbres on the matrix were present because the bioplastic fılm were not thoroughly mixed during the fıbrication process. Meanwhile, the SEM images at magnification 500× showed that the BF-0.70 produced in this study were smooth and had pores along the matrix with some agglomerations. The agglomerations were undissolved CF during the solubilisation in TFA.

EDX analysis was carried out for all four bioplastic films as shown in Table 4.3. It was indicated that all bioplastic films had a high content of carbon and oxygen which was attributed to the CF (Onovo et al., 2022). The negligible differences in FTIR spectra in Chapter 4.1.2.2 between CF and bioplastic films indicate that the fundamental functional groups in cellulose remain unchanged, supporting the EDX results showing stable carbon and oxygen compositions. In addition, the EDX analysis showed no detection of F- (fluorine) in the samples, which is consistent with the findings from the FTIR spectra in Chapter 4.1.2.2.

There were also traces of nitrogen elements, aluminium, and sodium elements, that can also be found in CF, as discussed in Chapter 4.1.3.1.

Table 4.3: EDX Analysis of Bioplastic Films

	CF			BF-0.10			BF-0.30			BF-0.50			BF-0.70		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
				Elemental composition (%)											
Oxygen	47.89	47.30	46.14	47.41	42.42	44.48	41.92	44.61	47.50	45.61	43.95	43.88	48.77	45.07	41.03
Carbon	50.53	51.50	51.89	51.62	56.16	55.53	56.26	53.84	50.87	53.87	54.39	56.12	51.23	52.9	57.55
Nitrogen	-	1.96	1.97	-	1.41	-	1.25	1.54	1.62	-	1.66	-	-	1.63	1.42
Aluminium	1.21	0.89	1.21	-	-	-	-	-	-	0.53	-	-	-	-	-
Sodium	0.37	-	0.37	0.87	-	-	0.57	-	-	-	-	-	-	0.40	-

4.1.4 Mechanical Properties Analysis of Bioplastic Films

Tensile tests were conducted on all bioplastic films, BF-0.10, BF-0.30, BF-0.50 and BF-0.70. It was observed in Figure 4.6 that the measured tensile strengths were 0.0075 MPa, 0.0364 MPa, 0.0660 MPa, and 0.0767 MPa respectively. Additionally, the Young's modulus values were found to be 0.2865 MPa, 1.040 MPa, 1.8491 MPa and 2.6524 MPa respectively. Based on Table 4.4, it was implied that BF-0.70 had the highest tensile strength and Young's modulus, followed by BF-0.50 and then BF-0.30. BF-0.10 had the lowest tensile strength and Young's modulus. This showed that of the four samples, BF-0.70 was the strongest and most rigid, whereas BF-0.10 was the weakest and least rigid.

Table 4.4: Tensile Strength and Young's Modulus of Bioplastic Films

Bioplastic Films	Tensile strength (MPa)	Young's Modulus (MPa)
BF-0.10	0.0075	0.2865
BF-0.30	0.0364	1.0404
BF-0.50	0.0660	1.8491
BF-0.70	0.0767	2.6524

BF-0.70 had the highest tensile strength and Young's modulus value. The higher the amount of CF immersed in TFA, the higher the amount of cellulose bonds within and between cellulose chains in the formed bioplastic film, which are proven to be crucial for improved mechanical properties of the bioplastic films (Wohlert et al., 2022).

The surface texture of the bioplastic films as shown in the SEM images as discussed in the previous chapter also affected the tensile strength of the bioplastic films. The texture of the bubble-shape protrusions on the surface caused mechanical

measurement samples to be non-uniform in term of cellulose distribution in the bioplastic films matrix, which affected the results of the mechanical analysis (Nguyen et al., 2022). The tensile strength and Young's modulus of the bioplastic film would be affected by the pores, provided they showed a weakness in the film's rigidity. The empty spaces or gaps within the material's structure which have been known as pores, can have an impact on a film's ability to endure stretching or deformation without breaking. This had an impact on the bioplastic film's overall rigidity, or its ability to maintain its shape and resist deformation. As a result, the tensile strength and Young's modulus are decreased (Zamrud et al., 2021).

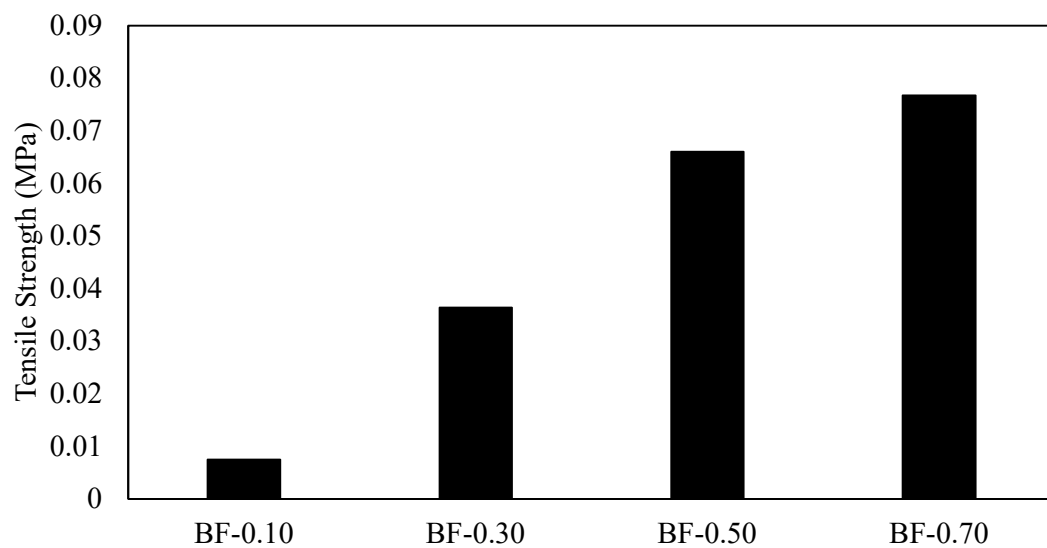


Figure 4.6: Tensile Strength of Bioplastic Films

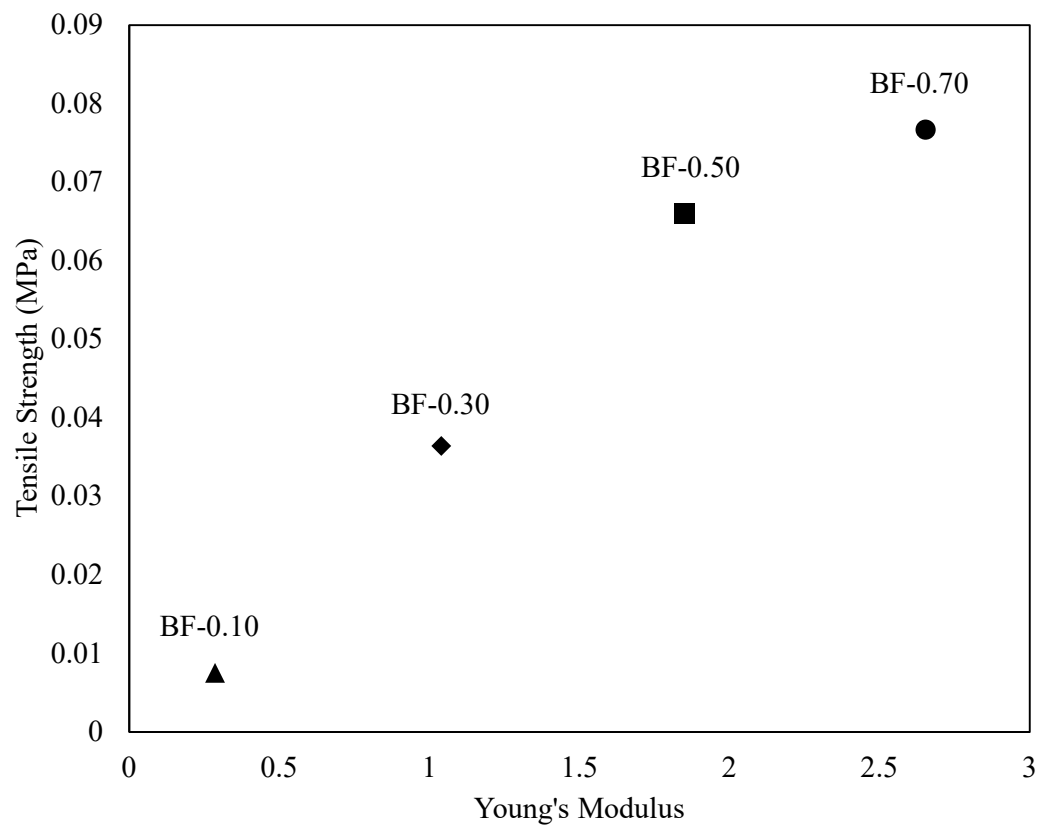


Figure 4.7: Tensile Strength vs Young's Modulus

By comparing the tensile mechanical properties of BF-0.70 and SSCMF bioplastic film from previous study (Syafri et al., 2019), it can be decided whether BF-0.70 performs similarly or differently in terms of its tensile properties, which will help in making thorough evaluation of its performance.

Table 4.5 below shows the mechanical properties of BF-0.70 and bioplastic film from SSCMF (Syafri et al., 2019). From the results, it was apparent that bioplastic films from SSCMF had better mechanical properties as compared to BF-0.70. One of possible reasons was the bioplastic film by Syafri et al. (2019) used starch as the matrix and the cellulose microfibrils as a filler that can enhance the mechanical properties of the bioplastic film whereas the film in this research did not incorporate any fillers in the matrix. One bioplastic film had cellulose fibres as fillers and starch as a matrix; another had no reinforcement of any kind, and both had displayed different properties and performance results, particularly in terms of mechanical properties.

Table 4.5: Mechanical Properties of Bioplastic Films of Sago Starch with Cellulose Microfibrils Bioplastic Film (Syafri et al., 2019) and BF-0.70

Bioplastic Films	Tensile Strength (N/mm ²)
Sago Starch with Cellulose Microfibrils	7.00
BF-0.70	0.07

These findings showed that bioplastic films formed in this research has weak mechanical properties. The values mentioned earlier indicated that the film has a low tensile strength does not meet the standard values of moderate grade of bioplastic, which ranges from 1 to 10 N/mm² of tensile strength (Nasir & Othman, 2021). Hence, the

bioplastic films produced in this study may not be suitable for applications that require high strength and durability.

4.1.5 Thermogravimetric Analysis (TGA)

The TGA curves for BF-0.30, BF-0.50, and BF-0.70 in **Figure 4.8** showed that there were slight weight losses of 10.17 % to 12.66 % mass percentage that occurred between 30°C and 200°C. These weight losses were caused by the moisture content evaporating (Steven et al., 2022) and the breakdown of weaker bonds in the structure of the bioplastic films (Obande et al., 2021).

The TGA analysis showed that BF-0.10, BF-0.30, BF-0.50 and BF-0.70 had rapid and significant composition in approximately 200°C and 400°C range. This can be attributed to the decomposition of cellulose in the bioplastic films (Guzman-Puyol et al., 2022). At this stage, BF-0.10 was the bioplastic film with the lowest initial decomposition temperature, at about 30°C. Conversely, at 193°C, BF-0.70 had the highest initial decomposition temperature. This was probably due to the higher content of cellulose in BF-0.70, as well as the good morphological properties possessed by BF-0.70 as compared to the other bioplastic films as discussed in Chapter 4.1.3.2.

The weight losses of approximately 12.35 % to 27.12 % corresponded to non-cellulosic component, around 380°C to 500°C for the TGA analysis, was found to be lignin based on previous research, which can be observed in all four bioplastic films (Trilokesh & Uppuluri, 2019). This supports the notion that lignin was still present as a component in the bioplastic as discussed in Chapter 4.1.2.2 and Chapter 4.1.3.1.

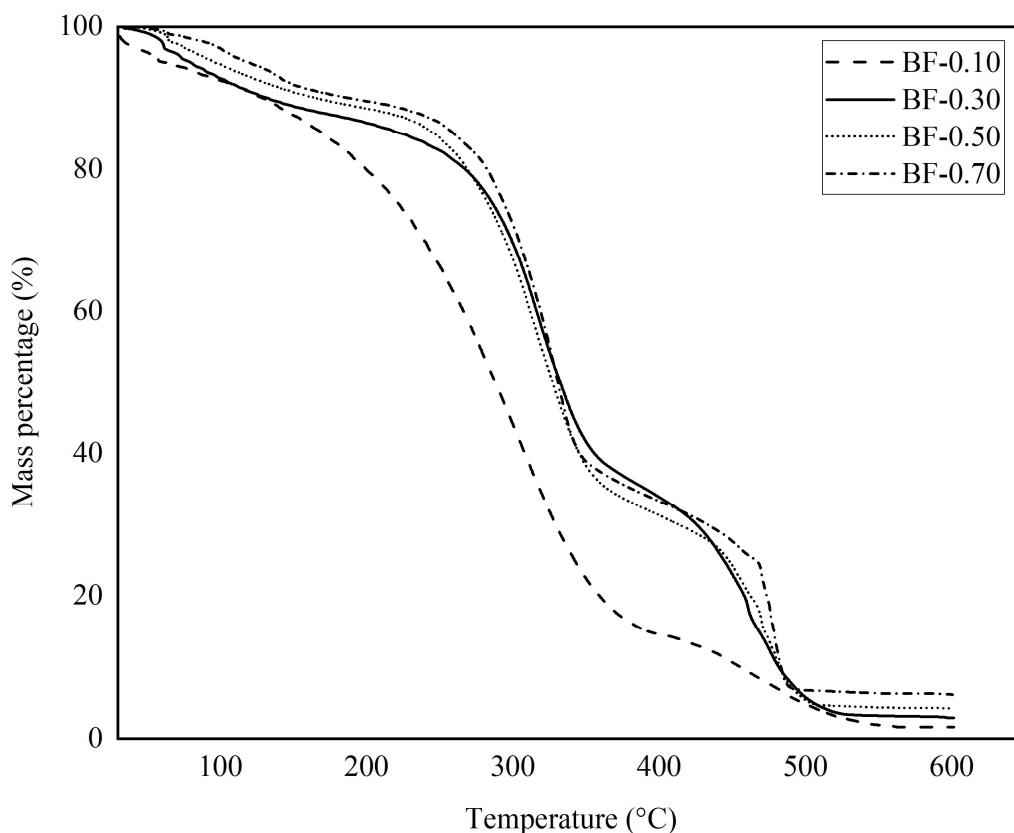


Figure 4.8: TGA Curve of BF-0.10, BF-0.30, BF-0.50 and BF-0.70

Figure 4.9 showed the estimated percentage of char residue of BF-0.10, BF-0.30, BF-0.50 and BF-0.70 after 600°C. It was observed that the residue increased as the amount of CF increased, hence the increase in amount of non-cellulosic components such as hemicellulose and lignin. The aromatic structures in lignin were thermally more stable and mostly remained in the char residue formed during heating (Liang et al., 2023). In addition, the thermal stability of the bioplastic film can also be determined by measuring the amount of char residue that is left over after heating. A larger mass of char residue, which is showed by BF-0.70, suggests that the bioplastic film is less prone to degradation and more thermally stable (Charles et al., 2022).

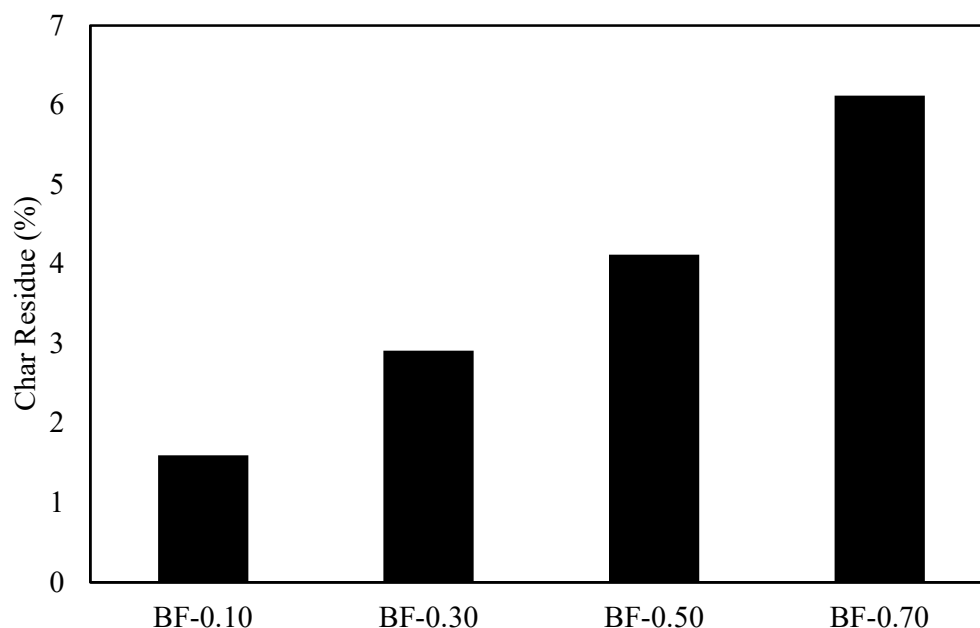


Figure 4.9: Char Residue of BF-0.10, BF-0.30, BF-0.50 and BF-0.70 after 600°C

In comparison, the char residue formed for bioplastic films from sago starch with cellulose fibres from SPW (Yacob et al., 2018) was around 0.73%, which was lower than this research's bioplastic film char residue, which was around 6.12% for BF-0.70. The lower char residue of the sago starch with cellulose fibre bioplastic film was probably due to the lower degradation temperature of starch (Syafri et al., 2019).

All in all, BF-0.10 had the lowest initial decomposition temperature of cellulose, which was the main part of the bioplastic film and the lowest char residue among all the other bioplastic films, which indicated that BF-0.10 was the least thermally stable. In contrary, the BF-0.70 had the highest initial decomposition temperature and the highest amount of char residue. This concluded that BF-0.70 was the most thermally stable.

4.1.6 Water Absorption

Water absorption capacity is an essential parameter that indicates how much moisture a bioplastic material can retain, which is a critical factor in determining its durability and suitability for certain applications (Nasution & Wulandari, 2021).

Figure 4.10 showed the water absorption of all four bioplastic films, BF-0.10, BF-0.30, BF-0.50 and BF-0.70. All four of the bioplastic films that had undergone the analysis demonstrated unfavourable water absorption characteristics, showing a notable tendency for high water absorption. This is probably due to the natural hydrophilic properties of the cellulose. Cellulose has hydroxyl groups (OH) which allows it to form hydrogen bonds with water molecules, leading to their strong affinity for water (Wohlert et al., 2022). The increment of pores presents as the mass of CF increased in bioplastic films had also influenced the water absorption of the bioplastic film. The SEM images had shown in Figure 4.5 that all bioplastic films in this research had noticeable pores and it became less obvious as the mass of CF to form bioplastic films increased. This had been contributing to the number of pathways for the water molecules to enter the bioplastic film which led to a faster water absorption process (Oluwasina et al., 2019).

As a comparison, for sago starch with cellulose fibres bioplastic film formed by Yacob and his team, the amount water absorption decreased as the number of cellulose fibres in the starch matrix increased. This was due to the restriction of the matrix chain mobility, which had resulted in lower ability of the water molecules to enter the bioplastic films (Yacob et al., 2019). Their lowest percentage for the amount of water absorption was 120%. Although BF-0.70 had lower amount of water absorption between the two bioplastic films, the amount of water absorption both bioplastic films were quite high as starch and

cellulose are both hydrophilic materials, meaning they had a strong affinity for water molecules.

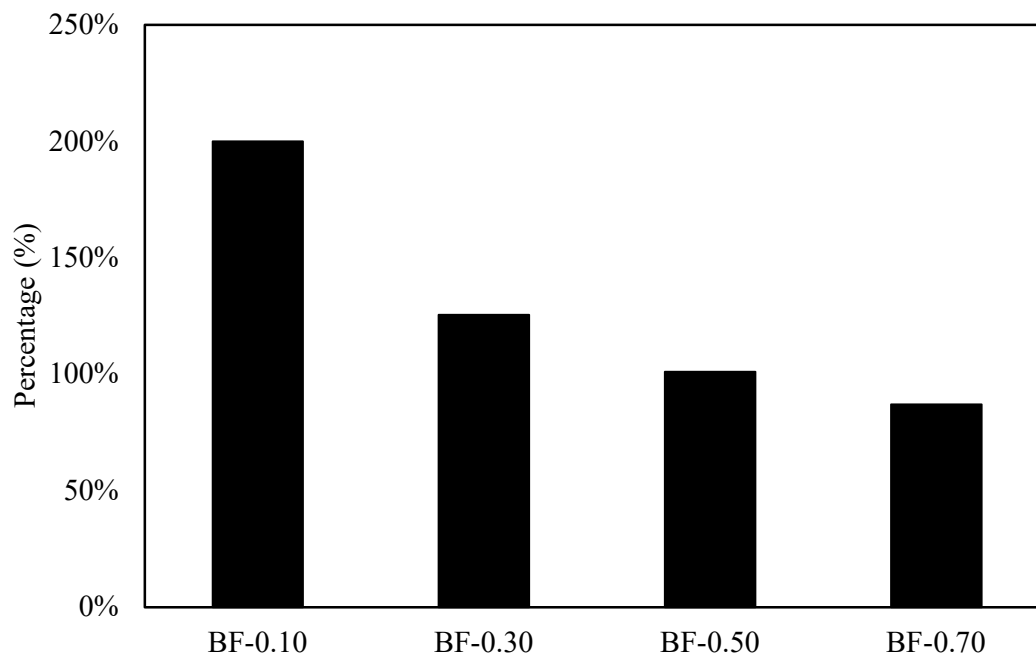


Figure 4.10: Water Absorption of BF-0.10, BF-0.30, BF-0.50 and BF-0.70

Therefore, the BF-0.70 sample in this analysis had the least water absorption compared to the other bioplastic films, mainly due to the smaller number of pores on BF-0.70 as compared to BF-0.50, BF-0.30 and BF-0.10.

4.1.7 Summary of Bioplastic Films Properties

In this chapter, the findings of experimental methods that include extraction of cellulose from SPW and CF solubilisation in TFA, were analysed and discussed. The investigation found that the alkaline and bleaching treatment to extract cellulose from SPW had partially remove the non-cellulosic components of the SPW. However, the CF was suitable to be utilised as raw material to be solubilize in TFA and had developed a free-standing transparent bioplastic film. The summary of the comparison of bioplastic films

were shown in Table 4.6. The bioplastic film with the best properties was marked with a (✓).

Table 4.6: Summary of Bioplastic Films Properties

Properties	BF-0.10	BF-0.30	BF-0.50	BF-0.70
Morphological (SEM)				✓
Mechanical				✓
Thermal Stability				✓
Water Absorption				✓

Overall, the morphological studies proved that due to the higher amount of cellulose solubilized in the TFA to form a bioplastic film, the bubble-shape texture appeared to decrease in size, and slight reduction in the number of visible pores were observed. The tensile of the film increased as the mass of CF increased, which can be attributed to the high amount of cellulose bonds within and between cellulose chains in the formed bioplastic film. BF-0.70 also exhibited the least amount of water absorption and the best thermal stability out of all the other films. Hence, in this study, 0.70 g of CF was chosen as the mass to be used in forming bioplastic films per 20 mL of TFA as it demonstrated good morphological property, least amount of water absorption and best thermal stability.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The extraction of cellulose from SPW was successfully done through alkaline and bleaching treatment. Observationally, bleached cellulose fibres extracted from SPW changed colour to white, which exhibited that most of the original non-cellulosic components had been removed. Free-standing bioplastic films were successfully formed by using the resulting CF. One standout discovery was the identification of the optimal CF mass, a critical parameter for forming bioplastic films. The findings found that solubilising 0.70 g of CF per 20 mL of TFA leads to a great improvement in morphological properties, tensile strength, and thermal stability, as demonstrated by the characteristics of BF-0.70.

Overall, observation of BF-0.70 demonstrated a significant reduction in bubble-shape protrusions, and the number of visible pores decreased significantly compared to lower CF masses. The significant improvement in tensile strength that results from this improved morphology is noteworthy, as demonstrated by the notable 90% increase in tensile strength of BF-0.70 when compared to BF-0.10. The reduction in structural irregularities and increased tensile strength can be ascribed to the higher cellulose content, which helps better intermolecular bonding within and between cellulose chains in the bioplastic films. Furthermore, the improvement in morphological properties correlates with the observed reduction in water absorption for BF-0.70, which showed a significant 150% decrease compared to bioplastic films with lower CF masses. The optimal CF mass of 0.70 g per 20 mL of trifluoroacetic acid (TFA) not only exhibited improved morphological

properties, increased tensile strength, and a reduction in water absorption, but also demonstrated good thermal stability, as it was observed that the char residue has tripled the amount of the char residue of BF-0.10.

All in all, this study is the first to use SPW for making bioplastic films by using TFA. By extracting cellulose and forming bioplastic films with TFA, a new way was discovered to repurpose SPW. This approach adds something new to existing research on cellulose-based bioplastics. It's a practical step towards sustainability and broadens the possibilities in bioplastic research.

5.2 Recommendations

Based on the findings of this research, certain recommendations can be made to optimize the production and enhance the properties of bioplastic films. Further research on the influence of volume of TFA on the production of bioplastic films with 0.70 g of CF. By altering the amount of solvent, the dissolution rate may be affected. The increase of the solvent may lead to a faster solubilisation process. By reducing the volume, the texture and other properties of the bioplastic films may be affected due to the high viscosity of the resulting solution after solubilisation process. The mechanical properties of the bioplastic films can also be improved by incorporating additional additives or reinforcements such as microcrystalline cellulose during the solubilisation of CF in the TFA (Bayer et al., 2019). By adding these additives, the mechanical properties and thermal stability of the bioplastic films may be altered. Lastly, the addition of trifluoroacetic anhydride (TFAA) to the mixture of TFA and CF can decrease the solubilisation time before the solvent casting process. Shorter solubilisation period can reduce energy consumption and improve process efficiency (Tedeschi et al., 2020).

APPENDIX

Appendix A: Journal Publication

Zabidi, N. F. & Lai, J. C. H. (2024). Physico-mechanical, morphological and thermal analysis of bioplastic films fabricated from sago pith waste cellulose fibres. *Journal of Engineering Science and Technology (JESTEC)*, 19(4), 1122-1141.
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