



Review on Jute Fiber Reinforced PLA Biocomposite

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Degree Thesis
Materials Processing Technology
2020

DEGREE THESIS	
Arcada	
Degree Programme:	Materials Processing Technology
Identification number:	
Author:	Netsanet Legesse
Title:	Review on jute fiber reinforced PLA biocomposite
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Commissioned by:	
<p>Abstract:</p> <p>The primary goal of this thesis was to gather scientific research data and review natural fiber reinforced biocomposites. Considerably, it analyzed the methodologies applied to produce biocomposites and presented the result. Plant fibers are composed of chemical substances called cellulose, hemicellulose, and lignin. However, cellulose is the main structural component of plant fibers used to reinforce biocomposites. Jute fiber is one of the most known plant fibers used to reinforce thermoplastics such as PLA. The reinforcement of jute fiber into the PLA matrix gives sustainable material called biocomposite. Biocomposites possess good mechanical properties, simultaneously they are renewable. However, to achieve good mechanical properties, performing surface treatment is crucial before reinforcing fibers into the matrix. Thus, alkali treatment is a common surface treatment method for plant fibers. In this method, NaOH is used to remove impurities from the surface of the plant cell wall. After alkali treatment, hydrophobicity and surface roughness increased on the plant surface wall, which increases fiber-matrix adhesion. Biocomposites can be produced using conventional compounding methods such as compression molding, injection molding, and extrusion. Besides, surface characterization of composites can be analyzed using DSC, FTIR, and SEM methods. Tensile test, flexural test, and impact test are the known mechanical testing methods in biocomposites. The tensile testing result shows, the tensile strength of biocomposite with treated jute fiber displayed higher tensile strength compared to untreated jute fiber. Rising in fiber loading increased the tensile strength of biocomposite. However, an increase in the concentration of NaOH reduced the flexural strength. SEM imaging of biocomposite displayed the presence of interconnected fibril networks in the biocomposite.</p>	
Keywords:	Biocomposites, Natural fibers, PLA, Jute fiber, Surface modification, Mechanical testing
Number of pages:	44
Language:	English
Date of acceptance:	

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LIST OF ABBREVIATIONS

APS	Aminopropyltriethoxysilane
DSC	Differential Scanning Calorimetry
FRPC	Fiber Reinforced Polymer Composite
FTIR	Fourier Transform Infrared
HDPE	High-density polyethylene
kt	kiloton
NFPCs	Natural fiber reinforced composite
PLA	Polylactic-acid
PP	Polypropylene
PS	Polystyrene
SEM	Scanning Electron Microscopy
T _c	Crystalline temperature
T _g	Glass transition temperature
T _m	Melting temperature
UN	United Nations

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1 INTRODUCTION

1.1 Background

Environmental concerns such as rising in an average global temperature, increasing sea level, and raising of petroleum price are pushing researchers in the field of material science to substitute synthetic materials with sustainable materials. Currently, sustainable development is one of the most frequently used term in the globe. However, generally accepted definition of the term sustainable development is defined in a non-binding action plan of United Nations (UN) concerning sustainable development as Agenda 21 states as: *‘Sustainable development is development that meets the needs of the present without compromising the ability of future generation to meet their own needs’* [1].

Biopolymeric materials obtained from different natural resources offer a potential help to the transition toward sustainable and green development. One of the advantages of biopolymeric materials is that it can easily decompose into the environment by breaking down into their constituents, such as carbon dioxide (CO₂) and water (H₂O). The processing time for decomposition may take from 100 to 1000 years, which truly depends on the environment where the decomposition takes place. The process of polymers biodegradation can be achieved by exposing them to environmental influences such as UV, oxygen, water, and microorganisms that will metabolize the polymer and produce harmless materials that do not affect the environment [2].

The term composite was used for the first time in 1500 B.C. At the time, the mixture of mud and straw were used to create strong and durable buildings. Straw sustained to reinforce to other composite products. Further, in ancient Egyptians and Mesopotamian settlers mud mortars were used to join mud bricks. Perceptibly, mud can be assumed as the first binding material used to fabricate plasters in ancient buildings, which is used till now in some parts of the world. However, in 1200 AD, the Mongols invented the first composite bow, made from a combination of wood, bamboo, bone, horns, and cattle tendons with natural pine resin [3].

In ancient times, natural resins derived from plants and animals were the only sources of glues and binders until scientists developed plastics. However, the modern era of composite began in the early 1900s, where plastics such as vinyl, polystyrene, phenolic, and polyester were developed. Hence, plastic materials took over the use of resins derived from plants and animals straight away. However, plastics alone were not strong enough to create some structure. Consequently, the idea of the first fiberglass, which is still used, introduced in 1935 by Owens Corning. Fiberglass creates an incredibly strong structure when combined with a plastic polymer. Hence, the idea of the fiber reinforced polymer (FRP) industry began [4].

Following many years, the need to use resins from plants and animals is becoming vital to make composites while the oil industry crises happened in the 1970s. Subsequently, intensive search for replacements of fossil-based raw materials led to finding materials from renewable sources. Although, at the time the reason was a high oil price, but later the arguments related to climate change; the increasing amount of CO₂ and greenhouse gases became the most important issue. Hence, biocomposites became an ideal choice in developing biodegradable material for numerous applications [5].

Currently, the industry of biocomposite is becoming more popular hence, the raw material to produce biocomposites can be obtained easily at a cheaper cost. Further, materials made from these materials are Eco friendly and environmentally sustainable. One of the known biocomposite is made from Polylactic-acid (PLA) and jute fiber. Jute fiber reinforcement in PLA matrix is becoming the potential biocomposite, which can be used for various applications. PLA is a biopolymer, which can be obtained from a renewable agricultural source such as corn starch, tapioca roots, and sugarcane. It is also known as a recyclable and compostable biopolymer [6].

PLA releases the least amount of CO₂ to the environment during production. Further, materials made from PLA reduces the emission of greenhouse gas during combustion, which is a serious global-scale problem. Recently, researchers are using plant fibers such as jute, coir, kenaf, bamboo, hemp, flax, ramie, and abaca to enhance the mechanical properties of PLA. On the other hand, jute fiber is the second largest natural fiber next to cotton, 100% biodegradable, and non-toxic. Furthermore, jute fiber is light in weight and has low density. To get better mechanical property and environmentally compatible performance, it is necessary to impart hydrophobicity of the jute fiber before mixing it with the PLA matrix [7].

1.2 Objectives

The objectives of this thesis work are the following:

1. To assess the positive effect of biocomposites over synthetic composites
2. To identify challenges linked with using natural fibers as reinforcement in biopolymeric matrix
3. Based on previous studies, to suggest natural fiber surface treatment methods
4. Based on previous researches, to investigate the effect of fiber loading in mechanical property of biocomposites
5. To explore the typical processing method and testing methods of biocomposites

1.3 Methodology

This thesis is written based on the literature review. The analysis and results are based on existing research studies focused on natural fibers and biopolymeric composites. The literature reviews consist of a scientific definition and the properties of biocomposites. Further, natural fibers as reinforcement in the biopolymeric matrix were discussed. Several articles, journals, and books were referred from databases such as ScienceDirect, ResearchGate, and Elsevier to write this thesis.

2 LITERATURE REVIEW

2.1 Composite

In recent years, fiber reinforced composite materials have gained much attention from researchers in the field of material sciences and engineering materials because of their excellent properties and wide applications [8]. Hence, reinforcement of natural fibers in polymeric matrix significantly increases the mechanical property of the entire composite, which is most industries desire [9].

Composite, shortened from composite materials, is a class of material combining two or more materials to form a material with better performance which has a downside using them individually [5]. These individual materials are called constituent materials, which include organic and inorganic compounds as a matrix and fibers as reinforcement. The result from these different components gives a new material with unlike characteristics than individual components. Since, the physical and chemical property of these constituent materials is significantly different [10].

Composite materials can be classified into three: polymer matrix composite, metal matrix composites, and ceramic matrix composite. However, polymer matrix composites have many advantages over the other two composites in terms of lower volume-to-weight ratio, a higher specific strength-to-weight ratio, the flexibility to form different shapes and sizes, resistance to corrosion, lower cost, simple manufacturing process, and recyclability [8]. In the polymer matrix composite process, the matrix surrounds the reinforcement material, and support to maintain their position, in response the reinforcement material enhance the mechanical and physical properties of the matrix [11].

Usually, to improve the mechanical and chemical properties of a polymer matrix composite material, the polymers can be reinforced using natural fibers, synthetic fibers, or both [12]. Consequently, the mixture of polymers with fibers resulting in a material with better mechanical property called fiber reinforced polymer composite. Fiber Reinforced Polymer Composites (FRPC), are composites made from hybrid materials. These materials are composed of a polymer matrix reinforced with an engineered or natural fiber [13].

2.2 Thermoplastic Biocomposites

Biocomposites, composite made from natural fiber, are a special class of composite materials. They are obtained from a renewable source that offers substantial sustainability, eco-efficiency, and green chemistry for the society. The most commonly used biocomposite material is made from wood, which is known as a thermosetting material. It consists of cellulose fiber, lignin as a binder, and hemicellulose as an adhesive material [5].

Biocomposite materials guide the development of the next invention of materials, products, and processes [14]. Biocomposite materials consist of a biodegradable polymer as a matrix and a natural fiber as a reinforcement [15]. Additionally, natural fibers have significant advantages over traditional synthetic fibers, such as eco-friendliness, biodegradability and recyclability; relative worldwide abundance and low cost; high toughness with low density [16].

Furthermore, biocomposites have good properties over synthetic composites in terms of their relative low density; high specific strength and stiffness; low negative impact on the environment which involves a reduction of CO₂ emissions simultaneously returning oxygen (O₂) to the environment; relatively good mechanical properties such as tensile modulus and flexural modulus; good surface finish of molded composite part; renewable resource; flexibility during processing, and minimum health hazard [7].

However, lower durability that is considerably improved with treatment; lower strength particularly impact strength; high moisture absorption which results in swelling; lower processing temperature; dependent on fibers property due to fiber type, harvest time, extraction methods are disadvantages of biocomposites over the synthetic composites. However, all of the above-mentioned disadvantages of biocomposites can be improved by different chemical and physical treatment of the reinforcement material [17].

The application of biocomposite can range from building materials to aerospace industries, and automotive industries. However, the application is still limited to other sectors. Hence, to expand the application of biocomposites, appropriate development is desired to the existing natural fibers. Furthermore, various experimental procedures of formulating natural fiber reinforced composite have been studied. The result presented, biocomposite materials are competitive with synthetic composite materials [14]. Similarly, studies have shown that natural fiber reinforced composites can be applied when high strength, high stiffness, and low component weight are required [18].

In Europe, NFPCs have been used extensively in automotive industries due to their environmental and economic benefits [2]. The European car industry uses around 80,000 tones of wood and plant fibers to reinforce composites, instead of using synthetic fibers like glass fiber and carbon fiber [19]. Although, to some extent synthetic fiber composites have better mechanical strength than NFPCs. However, recycling synthetic composites is difficult due to the separation inconveniency of their components, which contributes to a large amount of greenhouse gasses. Consequently, the interest of using NFPCs are growing rapidly in automotive application [20].

Biopolymers such as PLA are the main reason for the growth of bio-based plastic industry. The production capacity of PLA is predicted to increase by 50% by 2022. The production share of PLA in global bioplastics, in 2017 was 10.3% (212 kt) and presented in Figure 1 [5].

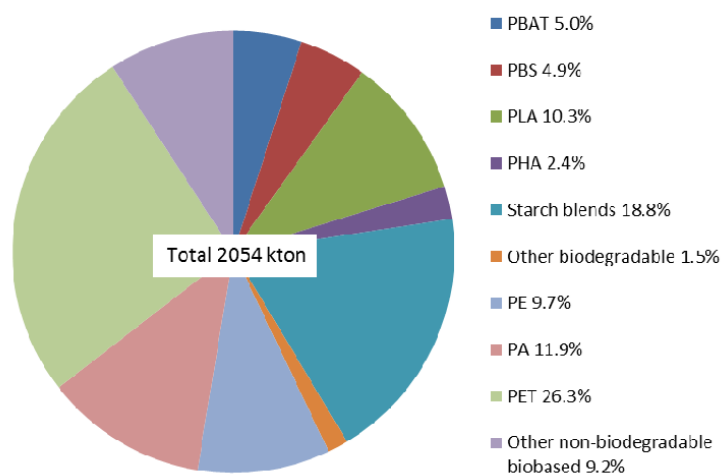


Figure 1. Global production capacity of bioplastics in 2017 by material type [5]

2.2.1 Polylactic-Acid (PLA)

Recently, PLA is becoming a green polymer which attracted researchers and industries in different sectors. Hence, it has biodegradable nature and it can be processed similarly to polyolefins [21]. PLA is a thermoplastic aliphatic polymer synthesized from renewable agricultural sources including starch-rich products such as corn, sugar beet, tapioca, and wheat [22]. Those plants are considered as CO₂ absorbing plants and in such a way reduce greenhouse emissions. Hence, in a controlled composting environment, PLA can break down into its constituent CO₂ and H₂O within three months. However, in a normal environment, with little oxygen and less light, the PLA bottle could take from 100 to 1000 years to decompose in a landfill or in a compost bin [23].

PLA was first synthesized in 1845 by Théophile-Jules Pelouze using the polycondensation of lactic acid. However, in 1932, Wallace Hume Carothers et al. developed a method to polymerize lactide into PLA, then patented by Dupont later in 1954 [5]. The class of PLA polymer belongs to aliphatic polyesters that can be produced either by carbohydrate fermentation or by chemical synthesis of lactic acid (LA) monomer [22]. Figure 2 shows the structure of L- lactic acid and D-lactic acid.

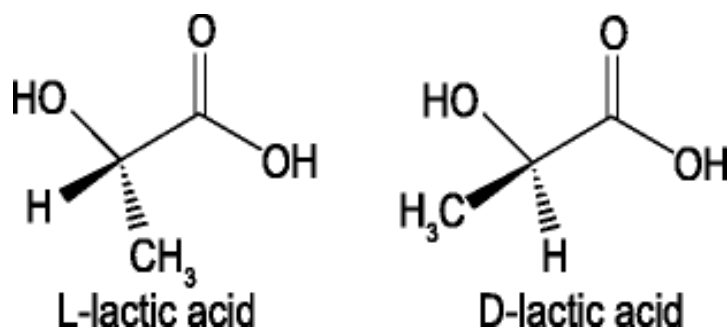


Figure 2. Enantiomers of lactic acid [5]

Furthermore, PLA is a bio-derived monomer having high mechanical properties, thermal plasticity, and good processing properties compare to some synthetic polymers. Hence, PLA can be for choice to conventional petroleum-based polymers. Currently, PLA is produced on a larger scale and used in various applications such as packaging, agriculture and textile materials. It is a good candidate for packaging materials because of its good optical property (i.e. transparency). Additionally, it has good mechanical properties such

as high stiffness and high tensile strength [21]. However, it has a high glass transition temperature (T_g) of around 61.5 °C that can lead to brittleness in the final product [24].

PLA has a higher value of tensile modulus and flexural modulus compared to petrochemical polymers, such as PS, PP, and HDPE. It has a melting temperature (T_m) between 150-175 °C and crystallinity around 40% [25]. In contrast, it has low thermal property that limits the application in the automotive industry or in the market that needs high thermal property. However, fiber reinforcement in the PLA matrix can improve the low thermal property and toughness of PLA [21].

Various polymers, additives, and fillers have been combined with the PLA matrix to enhance material performance, reduce cost, and expand the application of PLA. Currently, natural fiber reinforcing agents in the PLA matrix is considered as lower price of the resulting composite and creating materials that have potentially lower environmental impacts than the conventional synthetic polymers [6]. Table 1 shows the general characteristics of PLA polymer where, (*) is PLA from NatureWorks (2018), (**) Biomer P226, and (***) Omnexus, 2018.

Table 1. General characteristics of PLA and some commercial biopolymers [5]

Property	PLLA	PLA Ingeo 3052D* Nature-Works	PHB P226** Biomer	Bio-HDPE SHA7260 Braskem	Bio-PBS FZ1PM Mitsubishi Chemical Co.
Density kg/m ³	1.24-1.3	1.24	1.18-1.262	0.955	1.26
Tensile strength, MPa	15.5-150	62	40 (24-27**)	29	30
Modulus, GPa	2.4-4.14	3.6	3.5-4 (>1.14**)	1.35	0.63
Elongation at break, %	3.0-10.0	3.5	5.0- <u>8.0</u>	7.2	170
Charpy impact strength (notched, kJ/m ²)		0.3	2.7**	25	7 (Izod)
HDT, °C		55	59** (HDT-A)	74	95 (HDT-A)
T _g , °C	55-65	55-60	-15.0-(-5.0)	-110.0***	
T _m , °C	170-200	145-160	168-182	120-140	115

2.2.2 Mechanical Behavior of Biocomposites

Knowing the mechanical properties of a material is advantageous in the identification and classification of materials for different applications. The service life of most materials can be predicted by knowing the mechanical properties of the materials, which depends on the applied load [9]. However, the mechanical properties of biocomposite materials strongly depend on both the matrix and the fiber properties. Specifically, it is dependent on the fiber-matrix adhesion [26].

Composites can have anisotropic or isotropic property. Anisotropy is a property of a material in which the mechanical property of a material depends on the orientation of the fiber in the matrix, whereas isotropic property does not depend on the orientation. Consequently, anisotropic composites provide greater strength and stiffness than isotropic materials [13]. However, the mechanical property of biocomposites can be utilized to achieve a product with a specific property, that can be used in specific applications.

Moreover, the mechanical properties of composites depend on the shape of inhomogeneities, the volume fraction occupied by inhomogeneities, and the matrix-fiber interfacial adhesion. Furthermore, the strength of composite material depends on the brittleness or ductility of the reinforcement and the matrix. To analyze the failure property of a composite, failure mechanisms such as fracture of the fibers, fracture of the matrix, or failure of the fiber-matrix can be performed [27].

2.3 Natural Fiber Polymer Composite (NFPCs)

Currently, the application of NFPCs has increased in structural materials such as automobiles, aircraft, buildings, and roads [28]. NFPCs are composites consisting of a polymer matrix enhanced with high strength plant fiber, like jute, sisal, kenaf, oil palm, and flux [7]. Different factors can affect the characteristics and performance of NFPCs. The hydrophilic nature of plant fiber, the anisotropic property of plant fiber, and high fiber loading have a great impact on the properties of NFPCs [7].

High fiber loading is needed to attain good properties like tensile strength on NFPCs. However, excess fiber loading in the matrix leads to decrease the tensile strength. Another important factor that can have an impact on the properties and surface characteristics of NFPCs is the utilization of the processing parameters. Consequently, appropriate processing techniques and parameters should be selected to get good mechanical properties in NFPCs. The chemical composition of natural fibers also has a great impact on the properties of NFPCs, which is represented by the percentage of cellulose, hemicellulose, and lignin. Table 2 shows the chemical composition of some common natural fibers [7].

Table 2. Chemical composition of some natural fibers

Type	Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Reference
Bast (Stem)	Flax	71	18.6-20.6	2.2	[7]
	Kenaf	72	20.3	9	
	Jute	61-71	14-20	12-13	[29]
	Hemp	68	15	10	[7]
	Ramie	68.6-76.2	13-16	0.6-0.7	
Leaf	Sisal	65	12	9.9	
	Abaca	60.4	20.8	12.4	
	Banana	63-64	10-24	5	
	Pineapple	70-82	18	5-10	[29]
Seed	Cotton	82.7-92	5.7-6	0	[29]
	Kapok	64	13	23	
Fruit	Oil palm	65	-	29	[29]
	Coir	36-43	0.15-0.25	41-45	

2.3.1 Fibers

Fibers are reinforcing agents in a composite material and the main part of a composite system that carries structural load [7]. Fibers are divided into two main groups: natural fibers and man-made fibers. Generally, natural fibers are obtained from plants, animals, and mineral. However, man-made fibers are divided into synthetic and artificial. Usually, composite materials are made with synthetic fibers (e.g. carbon fiber, glass fiber, and aramid). However, the sustainable and environmental issues happening currently drives scientists in finding an effective solution from renewable and biodegradable materials, such as natural fibers [29].

Natural fibers are derived from renewable sources, which are completely biodegradable and non-toxic. Furthermore, using natural fiber does not influence the greenhouse effect at the same time they offer good mechanical and biochemical properties to the composite industry [2]. The basic classification of fibers is shown in Figure 3.

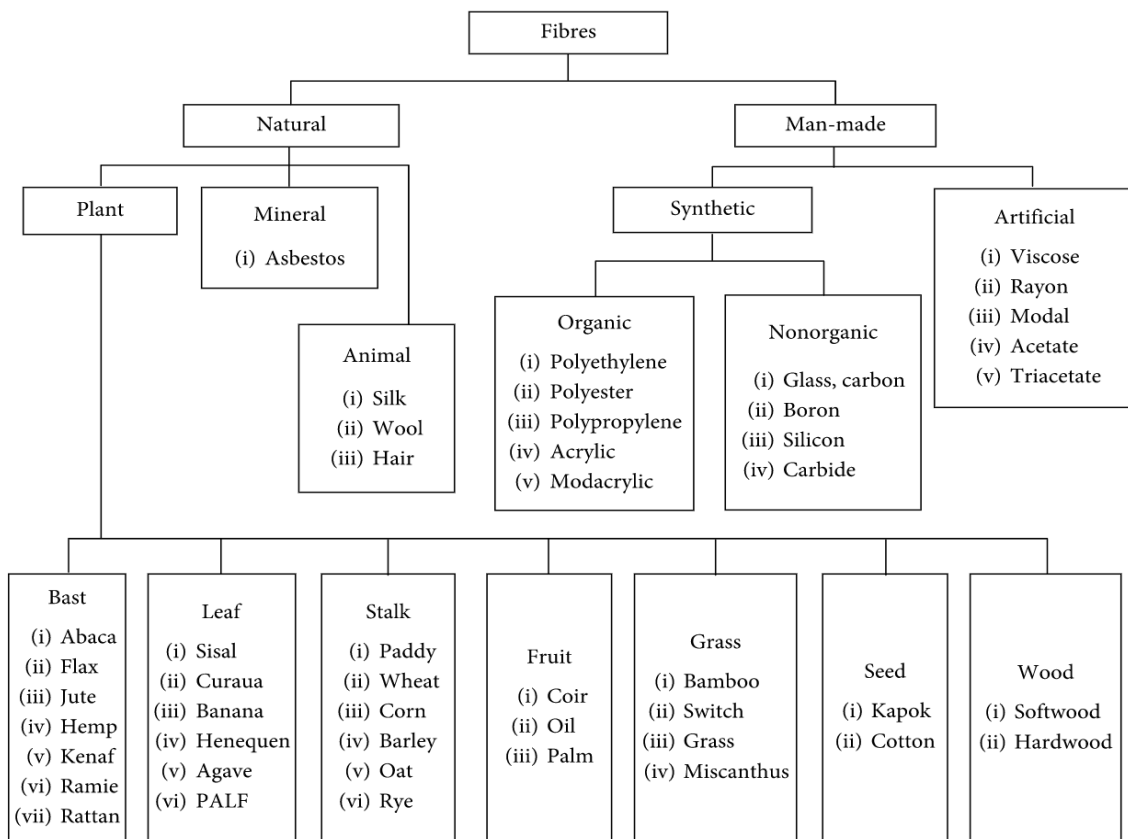


Figure 3. The classification of fibers [30]

2.3.2 Natural Fibers

The use of natural fibers was started in 7000 BC. Natural fibers can be defined as fibers originated from plants, animals, or minerals [7]. Hence, natural fiber obtained from plants is composed of cellulose, which is becoming a promising reinforcement agent in composite. Plant fibers, also known as lignocellulosic fibers, are formed from three chemical substances: cellulose (α -cellulose), hemicellulose, and lignin. Besides, plant fibers can contain different substances, such as waxes, pectin, inorganics, starch, and protein [29].

However, cellulose is the main structural component of plant fiber consisting of D-anhydroglucose ($C_6H_{11}O_5$) repeating units. Cellulose is hydrophilic and is a highly crystalline structure. Hemicellulose is the second major structural component of plant fiber which has a more complex structure than cellulose. It comprises a group of polysaccharides compiled of a combination of five and six-carbon ring sugars. It is very hydrophilic, soluble in alkali, and easily hydrolyzed in acids [31]. In contrast, lignin is a complex hydrocarbon polymer with both aliphatic and aromatic constituents. It is hydrophobic, insoluble in most solvents, and amorphous polymer, which stiffens the cell walls and acts as a protective barrier for the cellulose [29]. Annual production of plant fibers and their sources are shown in Table 3.

Table 3. Annual production of natural fibers sources [32]

Fiber source	World production (10^3 ton)	Origin	Fiber source	World production (10^3 ton)	Origin
Abaca	70	Stem	Linseed	Abundant	Fruit
Bamboo	10,000	Stem	Pineapple	Abundant	Leaf
Banana	200	Fruit	Ramie	100	Stem
Coir	100	Stem	Rice husk	Abundant	Fruit/grain
Flax	810	Stem	Sisal	380	Stem
Hemp	214	Stem	Wood	1,750,000	Stem
Jute	2500	Stem	Sugarcane bagasse	75,000	Stem
Kenaf	770	Stem			

2.3.3 Classification of Plant Fibers

Plant fibers can grow in various climates and can recycle CO₂. Since, plant fibers are mainly based on cellulose, they are completely biodegradable, and their production does not affect the ecosystem [33]. There are two general classifications of plants that produce plant fibers: primary plants and secondary plants. Primary plants are those grown for their fiber contents, whereas secondary plants are those the fibers come as a by-product from some other preliminary utilization [34].

Moreover, plants that produce cellulose fibers can be classified in various basic types such as, bast fiber, leaf fiber, fruit and seed fiber, core, grass, and reed fiber [7]. Bast and leaf fibers such as jute, flax, and ramie are called hard fibers, and most used ones [35]. Plant fibers come from lignocellulosic fibrous includes jute, coir, kenaf, bamboo, hemp, flax, ramie, abaca, and curaua [36].

2.3.4 Physical Properties of Plant Fibers

Plant fibers are characterized by their most important property such as air permeability, biodegradability, hygroscopicity, their ability to release moisture, and the fact that they are eco-friendly and lower flammability compare to synthetic fibers [33]. However, moisture affinity; poor interfacial adhesion; non-uniform dispersion; and degradation when heated over 200° C are the weaknesses of the plant fibers compared to synthetic fibers [37].

Furthermore, the hydrophilic and anisotropic nature of plant fiber is also a drawback in using them as reinforcement in the polymer matrix. Since, the hydrophilic nature of plant fibers affects the overall mechanical properties of the composite as well as other physical properties of the fiber [35]. However, the anisotropic property of plant fibers can be controlled by regulating fiber orientation through the die geometry [13].

Furthermore, as shown in Figure 4, the crystalline cellulose microfibrils in secondary walls (S2) determines the mechanical property of plant fibers. Additionally, the chemical composition of plant fiber after surface modification has a stronger impact on the mechanical properties of biocomposite [30]

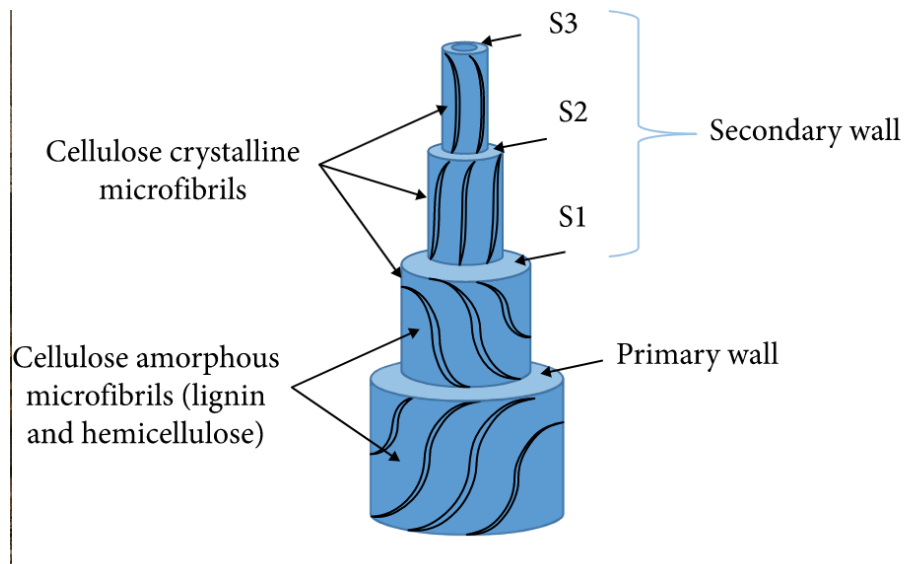


Figure 4. Schematic representation of plant fiber structure [30]

2.3.5 Mechanical Properties of Plant Fibers

Plant fibers are suitable to reinforce thermoset as well as thermoplastics due to their relatively high strength and stiffness and low density [35]. Plant fibers have lower density compare to synthetic fibers. The average density of plant fiber is 1.5 g/cm^3 whereas the average density of glass fiber is 2.5 g/cm^3 [37]. Furthermore, mechanical properties and structure of the plant fiber are also influenced by the area of growth, climate which the plant grows, and the age of the plant.

Furthermore, the mechanical properties of the plant fibers are mainly affected by the length and diameter of the individual fiber. Therefore, increasing the length of the fiber will increase fiber load-bearing efficiency. However, if the length of a fiber is too long, resulting in poor fiber dispersion due to fiber tangle, which reduces the overall reinforcement efficiency [38]. Further, the tensile strength of plant fiber is affected by the impurities found in the surface of the plant fibers [35]. Whereas, the young's modulus decreases with moisture content [38]. The mechanical properties of selected plant fibers and synthetic fibers are shown in Table 4.

Table 4. Mechanical properties of plant and synthetic fibers [38] and [39]

Fiber	Density (g/cm³)	Tensile Strength (MPa)	Young's Modulus (GPa)	Failure Strain (%)
Jute	1.3	300-700	20-50	1.2-3.0
Flax	1.45	500-900	50-70	1.5-4.0
Hemp	1.48	350-800	30-60	1.6-4.0
Bamboo	1.4	500-700	30-50	2
Sisal	1.5	300-500	10-30	2-5
Coir	1.2	150-180	4-6	20-40
E-glass	2.5	2000-3500	70	2.5
S-glass	2.5	4570	86	2.8
Aramid	1.4	3000-3150	63-67	3.3-3.7

2.3.6 Jute Fiber

Jute plant, known as the ‘golden fiber’ is one of the most used plant fibers. Jute plant has golden and silky shine color. It is used for sacking, burlap, and twine as a backing material for tufted carpets. It is an annual crop, sown in March and harvested in June to September, which takes 120 days to grow [40]. To grow jute plant, a warm and humid climate with a temperature between 24° C to 37° C is required. One hectore of jute plant consumes 15 tons of CO₂ and releases about 11 tons of oxygen to the atmosphere [39]. Growing jute plant demands a very small amount of chemicals and water which leads to less environmental damage. Using jute fiber is beneficial in manufacturing composite materials. Since, it promotes clean technologies, processes, products, and services that reduce environmental risk [41].

Jute fiber is the second most abundant natural fiber next to cotton in amount produced. It has a color of white or brown and a length of one to four meters. It is 100% biodegradable, non-toxic, inexpensive, and has proven to be effective and good reinforcement for thermoplastic and thermoset [42]. Jute plant grows mainly in India. It covers 58% of the world’s production, which is around 1.8 million tons per year. Other producing countries are Bangladesh, Nepal, China, and Indonesia [43].

Jute fiber has good thermal insulation property having a specific heat value of 1360 J/(kg.K) and its mechanical properties compare with glass fibers [25]. The major constituents of jute fiber are α -cellulose, hemicellulose, and lignin with a chemical composition of 58-68%, 20-24%, and 12-15% respectively. There are also some small quantities of components like fats, wax, water-soluble matter that does not affect its structure [44]. Jute fiber is hydrophilic by nature due to the presence of a polar group (-OH group) in its structure. Hence, the polar group forms hydrogen bonds by absorbing water molecules and this induces swelling in fibers [45]. The physicochemical properties of jute fiber are summarized in Table 5.

Table 5. Physicochemical properties of jute fiber [43]

Properties	Jute Fiber
Diameter (μm)	40–60
Cellulose content (wt%)	59–71
Lignin content (wt%)	12–13
Hemicellulose content (wt%)	14–20
Pectin (wt%)	0.2–0.5
Waxes (wt%)	0.4–0.8
Humidity (wt%)	12.5–13.7
Microfibrillar angle ($^{\circ}$)	7–9
Density (g/cm^3)	1.3–1.45
Elongation at break (%)	7.0–8.0
Tensile strength (MPa)	399–773
Tensile modulus (GPa)	10–30

2.4 Surface Modification of Plant Fibers

Surface modification is one of the essential means to improve the properties of the plant fibers. It improves fiber-matrix interfacial bonding, surface roughness, wettability, and hydrophilicity of the plant fibers [30]. Usually, the adhesion between plant fibers and a polymeric matrix is low due to polarity difference. For example, jute fiber is hydrophilic whereas the majority of the conventional polymers such as PLA, is hydrophobic [43].

Moreover, surface treatment is needed for plant fibers because they have some drawbacks when used as a reinforcement in composites. These drawbacks include incompatibility with hydrophobic polymer matrix; their high moisture absorption, and swelling properties which leads to cracks. Consequently, to eliminate those drawbacks chemical techniques have been attempted by researchers on the surface of plant fibers. Those methods are mainly focused to reduce the water absorption and improve the adhesion between natural fibers and polymeric matrix [46].

Accordingly, weak adhesion between plant fiber and polymeric matrix formed, which leads to weak mechanical properties of biocomposites [37]. Subsequently, surface treatment on plant fiber is required to improve the hydrophilic property of plant fiber. Thus, surface treatment of plant fibers can be done in three ways: physical treatment, chemical treatment, and physicochemical treatment. These treatments improve the adhesion characteristics of the plant fibers which consequently improve the mechanical properties of biocomposite [29].

2.4.1 Physical Treatment

Physical surface treatment changes the structural and surface characteristics of the plant fibers without changing the chemical composition of the plant fiber. This method influences the mechanical bonding of the composite by separating the fiber bundles into individual filaments and improve the fiber surface. Furthermore, it improves thermal properties, strength, modulus, and elongation of the plant fibers.

There are three known physical modification methods: simple mechanical, solvent extraction, and electric discharge [30]. Simple mechanical physical treatments such as stretching, can enhance the interface of plant fibers without changing the chemical composition of the plant fiber [26].

2.4.2 Chemical Treatment

Chemical surface treatment modifies and activates the fiber structure by using a hydroxyl group that can change the composition of the material by introducing new elements to interact with the matrix [30]. This method focuses on improving the hydrophilic properties of the plant fibers. On the other hand, chemical modifications improve the adhesion property of plant fiber, which consequently increases the mechanical properties of biocomposite [44]. Thus, chemical surface treatment methods include alkali treatment, coupling agents like silane, bleaching, enzymes, and peroxides [30].

Moreover, surface modification of plant fibers with chemical creates better compatibility between reinforcement and matrix [37]. On the other hand, chemical treatment methods utilize coupling agents to modify the surface composition of the fibers. Usually, chemical treatments are used to increase surface roughness or to reduce the hydrophilic property of plant fiber [26]. On the other hand, physicochemical treatments provide clean and fine natural fiber of fibrils that have very high cellulose content [30].

The main purpose of surface treatment on jute fiber is to remove unnecessary materials and to open the cellulose content. Usually, jute fiber contains unwanted materials in the surface known as gum. A process called degumming used to remove the impurities on the surface of jute fiber. By opening the cellulose content, it is possible to remove unnecessary materials from the surface. Consequently, chemical treatment makes fibers smooth by removing the gum from the surface and make them easy to adhere, durable, and flexible. Further, chemical treatment makes changes in the mechanical behavior of plant fibers, especially on their strength and stiffness [8]. Several fiber modification methods are shown in Figure 5 besides alkali treatment and silane treatment methods are discussed broadly.

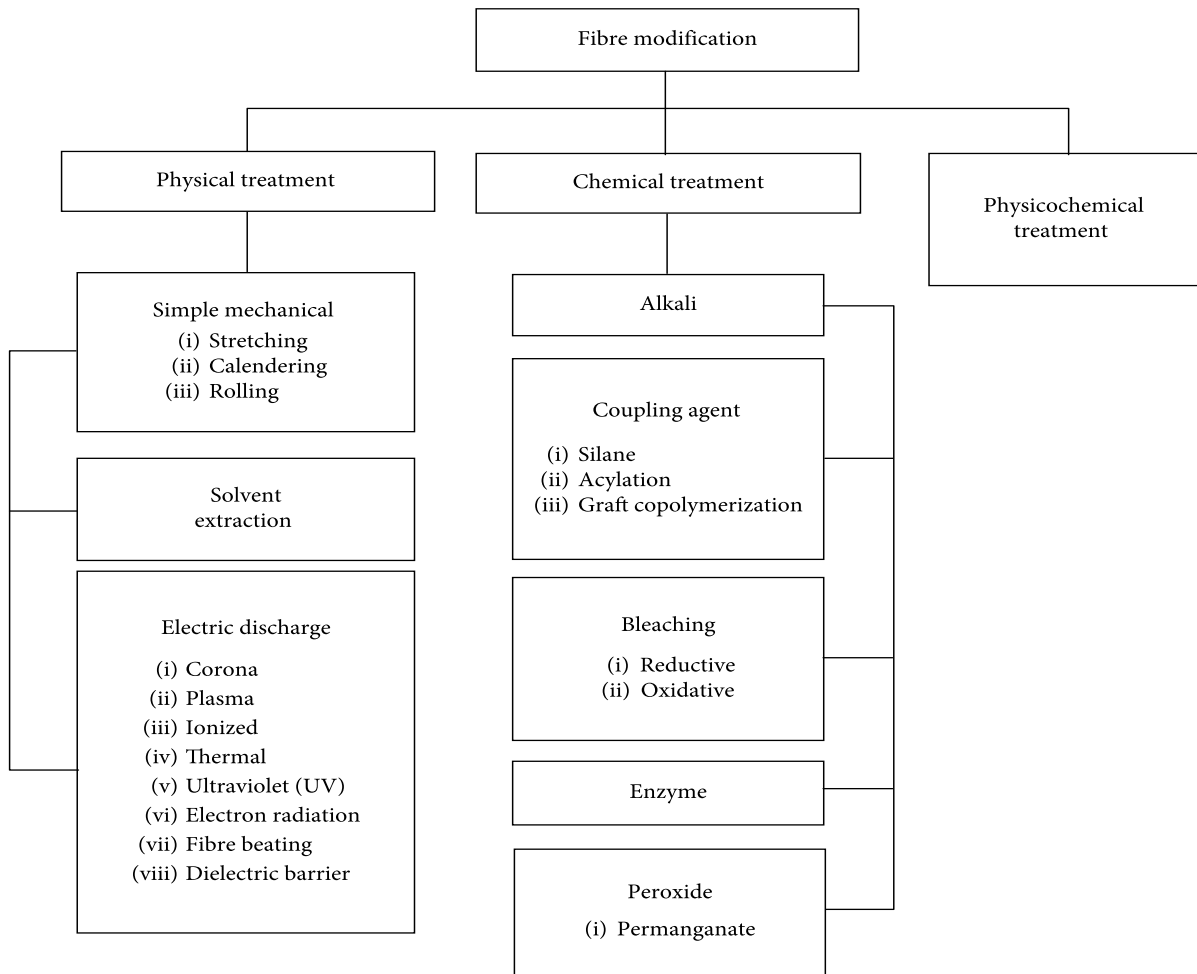


Figure 5. Fiber modification methods [30]

I. Alkali Treatment

Alkali treatment or mercerization is a widely used, most effective, and low-cost chemical treatment method for plant fibers. This method used Sodium Hydroxide (NaOH) as the primary chemical to treat plant fibers. The important feature of alkali treatment is the disruption of hydrogen bonding in the network structure, thereby increasing the surface roughness [44]. Consequently, this will increase the wettability of the fiber and increase the interfacial bonding between the fiber and matrix [5].

During alkali treatment, lignin and hemicellulose will partially remove. Whereas, pectin, wax, oils, and organic compounds that covers the exterior surface of the fiber cell wall will completely remove. This will activate the cellulose decomposition and expose short length crystallites [30]. According to studies, the result of NaOH treatment is observed to be increased after six hours of treatment. Thus, the modulus of jute fiber increased by 12% at four hours of treatment. However, it increased by 68% and 79% when treated for six and eight hours respectively [44].



During alkali treatment Hydrogen Peroxide (H_2O_2) can be used and is useful for bleaching cellulose materials. Bleaching with 30% purified H_2O_2 removes wax, fatty substance, and non-cellulosic substance such as lignin without changing the extracted fibers [44].

II. Silane treatment (SiH_4)

Silane is a coupling agent, which is a synthetic inorganic compound used to promote adhesion between dissimilar materials. It used as an adhesive in materials such as ceramics, metals, polymers, and composite [30]. Silane treatment can be used after alkali treatment to promote non-swelling behavior, high chemical resistance, and increase the tensile strength by cross-linking silane treated fiber and the matrix. Furthermore, both treatments can be used to improve the properties of plant fibers and enhance the fiber-matrix bonding in biocomposite [47]. Trialkoxysilanes and γ -aminopropyltriethoxysilane (APS) are the two types of silane coupling agents that are mostly used as coupling agents to reduce the number of hydroxyl groups, forming siloxanes that are adsorbed on to the fiber-matrix surface [30].

2.5 Processing Methods of Biocomposite

In the preparation of biocomposites with plant fibers, an important factor is the homogeneous distribution of the fibers into the polymer matrix. It permits greater contact between the components and improves the mechanical properties. Biocomposites can be processed as conventional synthetic composites. However, the processing temperature of biocomposites depends on the processing temperature of the fiber and the polymer. Thus, the selection of the processing technique is focused on obtaining the best properties of biocomposite for the desired application [16].

Plant fiber reinforced PLA biocomposites can be manufactured in the same way as the conventional composite. However, plant fibers have lower thermal resistance, so they must be processed at lower temperature, normally below 200°C. Further, the process method can be categorized as an open-mold or closed-mold process [5]. The processing methods of biocomposites include pultrusion, compression molding, injection molding, extrusion, filament winding, and vacuum infusion molding [32].

2.5.1 Pultrusion

Pultrusion is a manufacturing process in which reinforcing fibers impregnation with polymer matrix pulled through a die to form composites with a constant cross-section. The word pultrusion is formed with two words ‘pull’ and ‘extrusion’. Pultrusion is known to manufacture thermoset plastics. However, thermoplastics weaved composite by pultrusion molding with different forms of materials has been studied by various researchers. Pultrusion has three advantages which include suitable to produce the continuous composite with uniform cross-sections; suitable for mass production and low cost; and composite attains high mechanical properties due to the continuous fiber [48]. Figure 6 shows the manufacturing process of pultrusion.

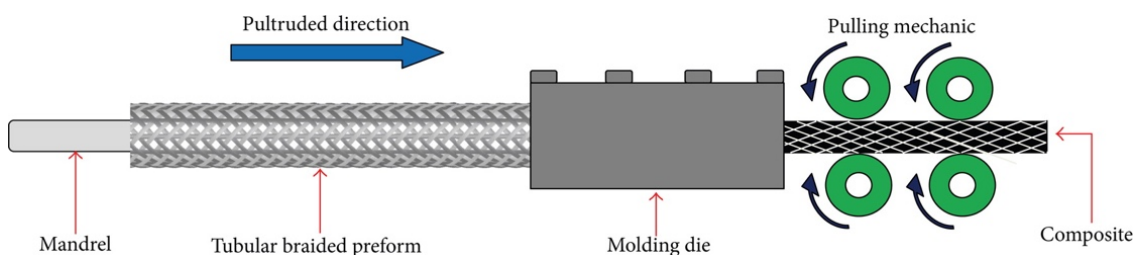


Figure 6. The schematic of the pultrusion process of braided composite [48]

2.5.2 Compression Molding

Compression molding is a process of applying pressure on a polymeric material placed in the lower side of a mold and pushed the upper part downward until it fits completely with its counterpart. Compression molding is a widely used processing method for manufacturing plant fiber reinforced polymer biocomposites. However, this method is used to develop medium to large size products which have a flat or simple shape [49]. Furthermore, Compression molding is advantageous because of the low capital cost, simplicity of the process, and can produce natural fiber reinforced PLA biocomposite without damaging the fiber during processing. However, the compression molding technique is time consuming and unsuitable for mass production [50].

In compression molding, the pre-heated molding material is placed in an open and heated cavity and the mold is closed by a hydraulic press. Additionally, pressure is applied to allow materials to keep contact with all the mold areas with a plug member and should be continued until the molding material has cured [25]. In the compression molding process raw materials need to be heated up and should be in the form of powder or pellets. Further, for thermoplastics, the temperature should be greater than T_g during the forming process [49].

2.5.3 Injection Molding

The injection molding machine is the preferred manufacturing method for mass production. Moreover, it is advantageous for high processability but, using injection molding degrade the fibers [50]. It has two main units: the injection unit and the clamping unit. In an injection unit, the thermoplastic material is melted and transfer to the clamping unit whereas, in the clamping unit, melted materials enter into a mold through a gate and runners using pressure. However, the product is cooled and kept in the closed mold until solidifies. Finally, the mold opened, and ejector pins inject the ready product [51]. From a fiber-polymer interaction perspective, using injection molding is better than extrusion due to higher pressures and enabling the contact between fibers and polymer closer [5].

2.5.4 Extrusion

The extrusion process can be carried out with a single screw or twin-screw extruder which uses either co-rotating or counter-rotating. For most short wood fiber containing thermo-plastic materials, extrusion machine is used to produce granules which can be used later for injection molding machine. Usually, a single screw extruder is used, if the mixing outcome does not affect the final product, whereas twin-screw extruder is used if good dispersion is needed in the final product. However, for lignocellulosic fiber, chopping or grinding the fibers to increase the bulk density and flowability helps the compounding of plant fibers with the matrix. Further, for moisture sensitive PLA, it is preferable to use cold air cooling instead of the common water bath method [5].

2.6 Characterization of Biocomposites

2.6.1 Fourier Transform Infra-Red (FTIR) Analysis

Fourier Transform Infra-Red (FTIR) analysis is a rapid, non-destructive, affordable, and user-friendly instrument used in analytical laboratories. FTIR test is used to obtain an infrared spectrum of absorption or emission of liquid, solid, or gas. However, for plant fiber reinforced composite FTIR analysis is carried out to assess the effect of chemical treatment on jute fiber [25].

2.6.2 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimeter (DSC) is a powerful, versatile, and thermoanalytical technique used to study the thermal properties of a polymer. The machine measures the amount of energy released or absorbed by a sample when it is heated, cooled, or held at a constant temperature. DSC machine measures T_g , T_m , and T_c as a function of temperature or time in a controlled atmosphere [52]. An example of a DSC plot of a polymer that undergoes T_g , T_m , and T_c are shown in Figure 7.

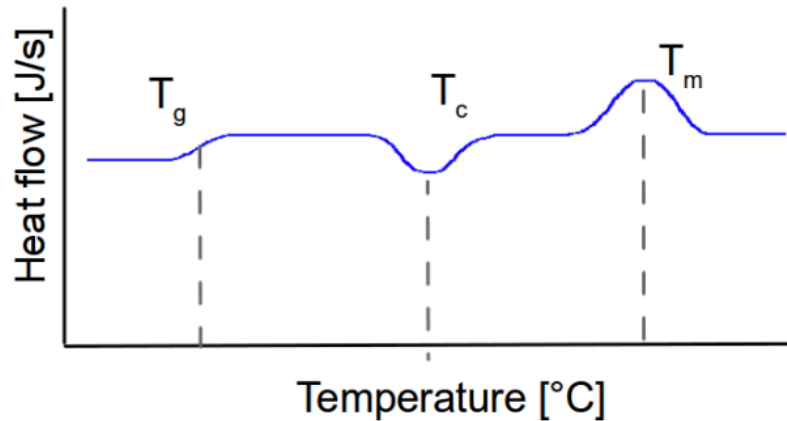


Figure 7. Heat flow Vs temperature plot for polymer that undergoes T_g , T_m , and T_c [52]

2.7 Mechanical Testing of Biocomposites

2.7.1 Tensile Testing

Tensile testing is one of the recognized methods used to identify the mechanical properties of materials. Tensile testing is used to determine the tensile strength, Young's Modulus, elongation at break, yield strength, ultimate strength, and fracture strength of materials. These properties are fundamental to determine the appropriateness of materials for a specific application or if the material might fail under specific stress [53].

2.7.2 Flexural testing

The flexural or bending test method is used to identify the fiber-matrix interfacial strength of a composite. This method is conducted to determine the mechanical property of the matrix and reinforced fiber composite material. Flexural test can apply to both rigid and semi-rigid materials. However, it cannot be applicable for materials that do not break in the outer surface of the test specimen within the 5% strain limit. The result from the test is plotted in the stress-strain diagram. The maximum fiber stress and strain are calculated from the increments of load. The test result includes flexural strength and flexural modulus. There are two types of flexural test methods: three-point loading and four-point loading. However, the three-point loading method is the most commonly used method for polymers [54].

2.7.3 Impact Strength

There are two standardized impact test methods to measure the impact energy of materials: Charpy and Izod impact test methods. Charpy impact test measures the energy absorbed by a standard notched specimen while breaking under an impact load. The ASTM standard for the Charpy impact test specimen has a dimension of 55 mm x 10 mm x 10 mm. Izod impact test measures the energy required to break a specimen by striking a specific size bar with a pendulum. The ASTM standard for Izod impact test specimen has a dimension of 75 mm x 10 mm x 10 mm. The difference between these two test methods are the position of the specimen, direction of notch face, the dimension of the specimen, type of hammer, and striking point. However, both are the most commonly used test methods to evaluate the relative toughness of a material in a fast and economic way. These techniques can be used in short as well as long fiber composites [25].

3 METHOD

In this section, methods in which different researchers used to produce jute fiber reinforced PLA biocomposite will be discussed. Moreover, surface treatment on jute fiber, preparation of biocomposites, and testing methods will be discussed by referring to existing researches.

3.1 Chemical Treatment Method

Mohanty et al. (2000) studied chemical surface modification of jute fiber and reviewed the improvement of the surface. During the process, five different types of surface modification detergents were used to wash the surface of jute fabric. In the beginning, dewaxing of the surface was done by washing jute fabric with 1 to 2 ratios of alcohol and benzene mixture for 72 hours at 50°C, followed by washing with distilled water and drying. The defatted fabric was treated with a 5% NaOH solution for 30 minutes at 30°C, then washed thoroughly with distilled water to obtain alkali treated fabric.

Rajesh et al. (2014) investigated the effect of alkali modification on the surface of jute fiber. Nevertheless, before the treatment jute fiber was soaked in the water for an hour, dried at 50°C, and lastly cut to 3mm length. Subsequently, jute fiber was treated with 5%, 10%, and 15% solution of NaOH for 6 hours at 70°C temperature with infrequent shaking and stirring. Afterward the alkali treatment, the fiber is neutralized with 50% acetic acid to remove any absorbed alkali and washed thoroughly. Finally, the alkali treated fiber was added to 1% H₂O₂ at room temperature and stirred for 45 minutes, washed with distilled water, and dried in the oven at 50°C until it has reached a constant weight [44].

3.2 Processing Method

3.2.1 Compression Molding

Yu et al. (2009, 2010) reported the use of compression molding to develop jute fiber reinforced PLA composite. In the process of making the composite two-roll milled pre-compounded sheets were hot-pressed at 20 MPa and 170°C for 4 minutes and cooled at room temperature at 5 MPa pressure. Additionally, Hu et al. (2010) developed randomly oriented short jute fiber which lengthen 10–15 mm reinforced PLA bio-composites using the film stacking method. Jute fibers with varying fiber volume fractions (30, 40, and 50%) were stacked alternatively between PLA films and placed between a compression molding with a pressure of 1.3 MPa at 170°C for 10 min to obtain 4–5 mm thick bio-composites [49].

Ramchandran et al. (2016) also reported how a compression molding machine was used to produce jute fiber reinforced PLA composite. Thus, a ratio of 20% jute fiber and 80% PLA resin in 90-degree orientation were placed in the mold and preheated at 165°C for three minutes under no pressure, and after that 1.5 MPa pressure was applied for three minutes at the same temperature. Further, the mold was cooled by circulating cold water and kept for a duration of 10-12 hours [25].

3.2.2 Injection Molding

Rajesh et al. (2014) developed PLA granules using a vertical injection molding machine with two heating zones. The samples were prepared with different weight proportions (5%, 10%, 15%, 20%, and 25%) of jute fiber content and PLA matrix with an operating temperature of 190-210 °C. However, before making the composite the fiber was treated with different concentrations of NaOH in successive alkali treatment. Consequently, the samples were air-cooled at room temperature and prepared for tensile testing as per ASTM standard [44].

4 RESULT AND DISCUSSION

4.1 Physical Properties of Composites

According to Rajesh et al. (2014) reduction on the density of composites was exhibited with a 15% concentration NaOH treated fibers followed by H₂O₂ bleaching. The result might originate from the removal of non-cellulosic materials from the surface of the jute fiber. Accordingly, there was a 24% density reduction in the composite with a concentration of 15% NaOH treated fibers followed by bleaching at 25% weight fiber loading. Furthermore, the fiber diameter was reduced by 13.7% and the weight has reduced by 21%. According to Rajesh et al. (2014), the result is due to the removal of lignin, pectin, and hemicelluloses present in the cell wall [44].

Table 6. Summary of surface treatment and improvement on the properties of jute fibers reinforced PLA composite

Type	Modification performed	Results and improvements on the properties	References
Silane treatment	Treatment with potassium permanganate	Higher thermal stability, increased T _m and T _s but decreased impact strength	[45]
Alkali treatment	5% NaOH	Color of the fiber changes from brown to dark brown	[44]
Alkali treatment	15% NaOH	Fiber diameter reduced by 13.7% and weight has reduced by 21%	[44]
Alkali treatment	15% NaOH	Least density of a composite was attained	[44]
Alkali treatment	NaOH, 60% fiber loading	Pre-treatment with NaOH resulted in an improvement in the stiffness of composite	[55]
Alkali treatment	Dewaxing, bleaching, and grafting with vinyl monomers	A decrease in moisture affinity	Siddique et al.
Silane treatment		Improved wettability of natural fiber during composite fabrication	Bisanda et al.

Furthermore, in the report of Wang et al. (2019), chemically treated jute fiber attained around 25% weight reduction and analysis made in SEM displayed the critical structure of jute fiber became prominent after the removal of impurities through chemical treatment as shown in Figure 8 [8].

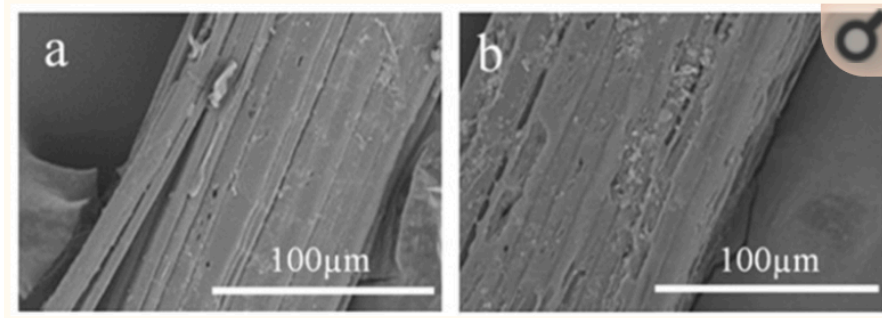


Figure 8. SEM of (a) raw jute fiber and (b) treated jute fiber under 1000X magnification [8]

4.2 FTIR Result

After assessing chemically treated jute fiber in FTIR, Wang et al. (2019) reported the chemical composition of jute fiber displays no change in the chemical bonds [8]. Furthermore, Ramchandran et al. (2016) examined PLA, jute fiber, and jute fiber reinforced PLA composite individually in the FTIR machine. Accordingly, the result of jute fiber reinforced PLA composite showed the same functional group which is found in the FTIR test of jute fiber and PLA. Consequently, the researcher concluded there was no chemical reaction between the fiber and the resin [25].

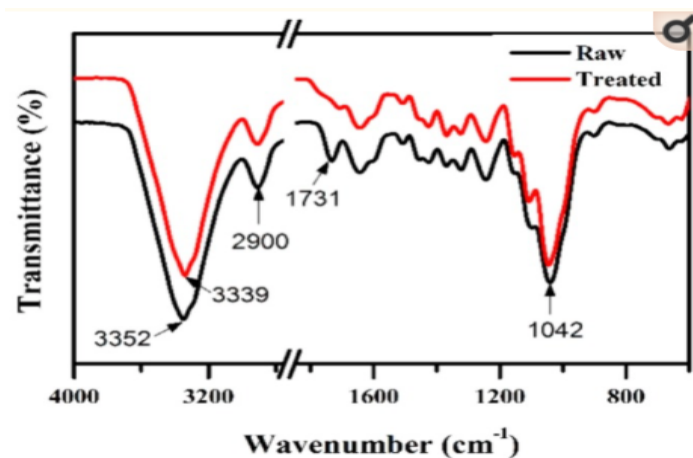


Figure 9. FTIR spectra of raw and treated jute fiber [8]

4.3 DSC Result

According to Ramchandran et al. (2016) the glass transition temperature of jute fiber and PLA before mixing were 61.04°C and 153.68 °C respectively. However, the glass transition temperature for jute fiber reinforced PLA composite was reduced by 7 °C and became 146.15 °C. Nevertheless, the reduction of the temperature does not affect the composite when applied to industrial roofing sheet [25]. The DSC test of jute fiber reinforced PLA composite is shown in Figure 10.

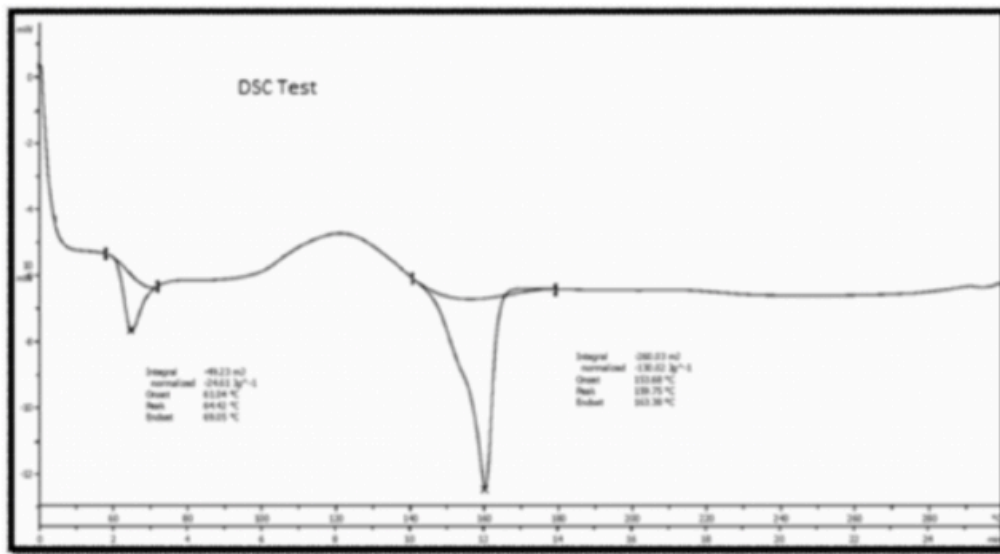


Figure 10. Jute fiber reinforced PLA composite DSC test graph [25]

4.4 SEM Characterization of Fractured Surface

Scanning electron microscopy (SEM) is a powerful and versatile tool for material characterization. Rajesh et al. (2014) has studied the tensile fractured surfaces of jute fiber reinforced PLA composite with 25% weight fiber loading. Figure (11 a) shows the SEM image of untreated jute fiber reinforced PLA composite and Figure (11 b, c, and d) shows the SEM image of composites with successive alkali treatment of NaOH with 5%, 10%, and 15% concentration respectively.

Accordingly, the tensile fractured surface of untreated jute fiber reinforced PLA composite has exhibited large fiber pullouts, which might be an indication of poor fiber-matrix adhesion. Jute fiber treated with a 5% concentration of NaOH has exhibited poor interaction of fiber with matrix due to lower concentration of NaOH, which might not remove much lignin and fatty acids from the fiber surface.

However, jute fiber treated with a 10% concentration of NaOH exhibited fiber breakage rather than pullout, which expresses better stress transfer between fiber and matrix. Finally, jute fiber treated with 15% concentration of NaOH has caused fiber damage which indicated weak bonding between fiber and matrix besides no stress transfer took place among the fiber and matrix [44].

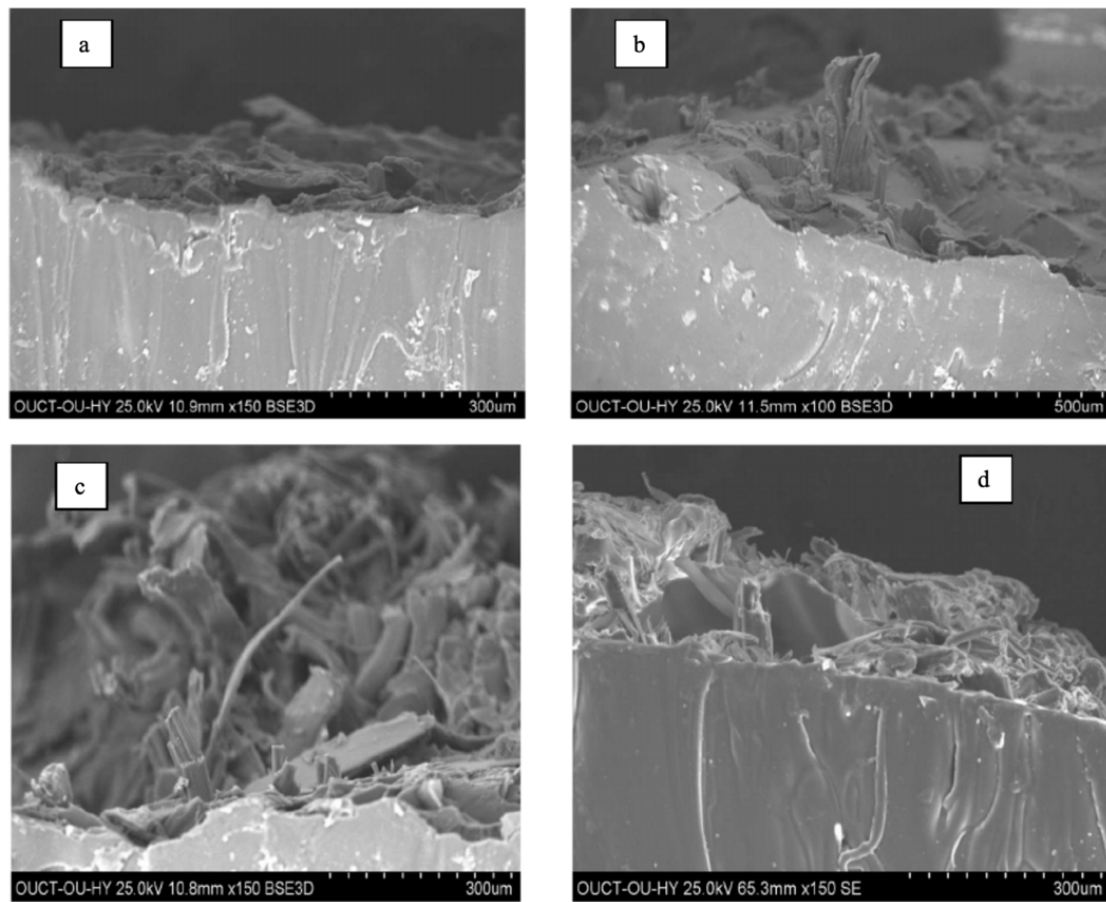


Figure 11. SEM image of jute fiber reinforced PLA composite tensile fractured surface [44]

4.5 Mechanical Testing Result

4.5.1 Tensile Testing

Fiber loading and surface modification on plant fibers are key factors for increasing the tensile strength of biocomposites. According to Rajesh et al. (2014) the tensile strength of untreated jute fiber reinforced PLA composites exhibited less strength compared to the pure PLA. However, the tensile strength of composites was increased on the treated jute fiber until a concentration of NaOH reached 10%. Nevertheless, for a concentration above 10%, the tensile strength was decreased. Consequently, the highest tensile strength was obtained for 10% NaOH concentration at a fiber loading of 25%. Hence, the tensile strength of treated jute fiber reinforced PLA biocomposite at 25% fiber loading was found 7.7% higher than the pure PLA [44].

Additionally, the researcher observed an increase in fiber loading increases the tensile strength of biocomposites due to good adhesion between fiber and matrix. However, increasing the fiber content after reaching maximum fiber loading reduced tensile strength since there will be an excessive formation of fiber-fiber interaction than fiber-matrix interaction [56]. Furthermore, Rajesh et al. (2014) reported, the addition of 25% weight of fibers to the PLA matrix has radically reduced the elongation at break by 54.54%. However, increasing the fiber loading and concentration of NaOH during fiber treatment significantly increases the tensile modulus by 125%.

4.5.2 Flexural Strength

Gunti et al. (2015) has reported the flexural properties of jute fiber reinforced PLA composite. Accordingly, there was an initial drop in the flexural strength at 5% fiber loading of untreated jute fiber reinforced PLA biocomposite. According to the researcher, the reduction in flexural strength was due to poor stress transfer between fibers and matrix. However, for treated jute fiber reinforced PLA biocomposite the flexural strength increased compare to the untreated fiber and pure PLA. Thus, the maximum flexural strength (18%) was obtained by a 10% concentration of NaOH/H₂O₂ treated jute fiber and 20% fiber loading.

However, with a further increase in the concentration of NaOH, there was a radical fall in the flexural strength. Furthermore, Gunti et al. (2015) has found an increase in flexural strength with an increase in the fiber loading up to 20% but, after that the flexural strength was reduced. According to the researcher, an increase in the flexural stresses occurred due to good interfacial adhesion between fiber and matrix. Hence, the flexural strength of composites depends on the modulus of the fiber and matrix. Since, jute fiber has higher modulus, increasing fiber content in composites increases the modulus of composites [53].

4.5.3 Impact Strength

Ramchandran et al. (2016) reported the average result of five sample specimens for each Izod and Charpy test and the average value was 9.2 Joules and 37.6 Joules respectively. Furthermore, Gunti et al. (2015) reported the impact strength of untreated jute fiber reinforced PLA biocomposite was increased with fiber loading compared to pure PLA. Consequently, the impact strength of composites with untreated jute fibers was 22.3% higher than pure PLA. However, surface treated jute fiber reinforced PLA biocomposites showed less impact strength compared to untreated jute fiber composite, but the strength was higher than pure PLA.

Moreover, the consistency in fiber dimension, better homogeneity obtained by bleaching, and increasing fiber reinforcing percentage increases the impact strength of composites [54]. The negative effect of surface treated fiber composite in impact strength was attributed to the fact that the surface treatment improves the fiber-matrix adhesion, which leads to the fracture of fibers rather than pullout during mechanical shock [53].

5 CONCLUSION

Biocomposites made from renewable raw materials such as jute fiber and PLA are gaining more attraction in several applications. Plant fiber reinforcement into the PLA matrix gives biocomposites good mechanical properties like strength and stiffness. Furthermore, using plant fiber as a reinforcement reduces the cost of the materials, reduces the carbon footprint, and decomposes easily, compared to glass fiber. However, plant fibers have a negative effect associated with fibers-matrix interfacial adhesion, which is the main challenge to use plant fibers as a reinforcement. Nevertheless, to achieve good reinforcing ability, surface treatment in plant fiber is crucial. Since surface treatment increases the surface roughness of plant fibers which can lead to proper bonding between fibers and matrix. Consequently, proper bonding enables the stress transfer from fiber to matrix, which is the means for achieving good mechanical properties in biocomposites.

Hence, better mechanical properties were obtained by performing alkaline treatment on jute fiber which lead to good interfacial adhesion between fiber and matrix. Moreover, surface modification of jute fiber with NaOH and H₂O₂ had significantly improved the mechanical properties of biocomposites such as tensile strength, flexural strength, and elongation at break compared to biocomposites with untreated jute fiber. However, excessive removal of non-cellulosic material by increasing the concentration of NaOH more than 10% weakens or damages the fiber which consequently reduces the strength of biocomposites. Furthermore, high fiber loading is required to attain good mechanical properties on biocomposites. Thus, fiber loading more than 25% decreases the tensile strength and elongation at break of biocomposites.

In conclusion, the above results show jute fiber reinforced PLA biocomposites have the ability of substituting non-degradable synthetic fiber composites. However, to achieve good properties in biocomposites, it is necessary to perform appropriate surface treatment and suitable processing techniques with accurate parameters. Consequently, alkaline treatment and compression molding are found to be suitable in making jute fiber reinforced PLA biocomposite. However, further studies should be undertaken for different fiber volume fraction and fiber orientations. Finally, choosing appropriate mechanical testing is a means to compute the results.

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