INVESTIGATION OF MECHANICAL AND PHYSICAL PROPERTIES OF COMPOSITE MADE OUT OF KITHUL FIBER WITH WASTE POLYETHYLENE

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Thesis/ Dissertation submitted in partial fulfillment of the requirements for the degree Master of Science/ Master of Engineering in Civil Engineering

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Name of the supervisor: Prof. R.U. Halwathura

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Name of the supervisor: Dr. (Mrs). G. Harsha Galabada

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Abstract

In Sri Lanka, waste polyethylene leads to significant social and environmental issues. The optimal solution lies in the advancement of fiber-reinforced polymer matrix composites. Natural fibers made from agricultural waste have several benefits, including low cost and density, non-toxicity, and reduced concern for the environment and waste disposal issues.

The research study was conducted to determine the diameter, density, water absorption, SEM, FTIR, and tensile strength of these selected natural fibers.

The values for Palmyra and banana fibers obtained maximum average diameter and lowest average diameter are 523.0138 m and 156.996 m, respectively. Sisal fiber has the highest average density (1.159 g/cm3), and Watakeiya fiber has the lowest average density (0.762 g/cm3). The results of water absorption tests performed on seven fibers were analyzed. Banana and Watakeiya fibers had the highest water absorption value, while bamboo and Palmyra fibers had the lowest. Banana and sisal fibers had tensile strengths of 772.5 MPa and 586 MPa, respectively. Kithul fiber was selected as a natural fiber for the investigation.

Composite sheets were created using a hot press machine and kithul fibers of various weights with the appropriate polymer matrix, processing temperature, processing pressure, and kithul fiber length. The tests were conducted following ASTM D790 and D3039, respectively. When the kithul fraction was 10% of the total weight, the processing temperature was 150°C, the processing pressure was 30 tons, and the kithul fiber length was 10mm, the maximum tensile strength, and flexural strength were observed as 12.237 MPa and 12.51 MPa, respectively. The final product has an impact resistance of 66.67J/m and flammability of 20.85mm/min, respectively. The final application of this product cannot yet be defined. Further studies are suggested to finalize the application of this product.

Keywords: Kithul Fiber, Waste Polyethylene, Physical Properties, Mechanical Properties, Sustainable Construction Material

Acknowledgment

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Abbreviations

NFCS - Natural Fiber Composites

SEM - Scanning Electron Microscopy

FTIR - Fourier-Transform Infrared Spectroscopy

HDPE - High-Density Polyethylene

LDPE - Low-Density Polyethylene

LLDPE - Linear Low-Density Polyethylene

UTS - Ultimate Tensile Strength

PP - Poly Propylene

PS - Polystyrene

PLA-EFB - Polycyclic Acid 3051D with Palm Empty Fruit Bunch Fiber

PLA-KE - Polycyclic Acid 3051D with Kenaf

PS-KE - Polystyrene with Kenaf

CHAPTER 1

1.1 Introduction

Plastic pollution pertains to the buildup of discarded plastic materials in the environment, causing harmful consequences for humans, animals, and their ecosystems [1]. Substances that negatively impact a population's health, activities, or survival are known as pollutants [2]. Due to human activity and natural phenomena, thousands of tons of pollutants get released into the atmosphere daily. Much more hazardous pollutants are those that people discharge into the atmosphere [3]. Plastics that act as pollutants can be classified into three categories based on their size: micro debris, mega debris, and microplastics. Studies, such as the one conducted by Obebe S.B. in 2020, have found that mega-plastics and microplastics have been observed in the Northern Hemisphere with the highest densities. These concentrations are often found near the currents that carry the plastic debris. Additionally, plastic debris can be observed along the coastlines of various islands [1]. Mega-plastics and micro-plastics are frequently utilized in the production of footwear, household items, and packaging materials (such as plastic bottles and bags). Later, it ends up that these are being dumped in landfills or washed off of ships. Fishing materials, commonly used in fishing activities, can also be discovered on isolated islands, even in remote locations. The terms "microplastic," "mesoplastic," and "macroplastic" are still used to describe these.

Plastics are durable and expensive. These factors contribute to the high level of human plastic production and the steadily rising demand for plastic. Human activity has the potential to damage both natural ecosystems and the existence of humans [4]. This is shown by the usage of plastics for packaging, such as bottles, bags, and other items made of plastic, which, after being used, are found to have been carelessly discarded without thought to the effects. If not adequately discarded or disposed of, these plastic wastes cause pollution and choking hazards for humans, animals, and their habitats. Consequently, plastic pollution can impact land, water, and the oceans [5].

Most plastics degrade over relatively long periods due to their chemical composition and excellent resilience to many natural disintegration processes. The significant

increase in plastic pollution in the environment has profoundly impacted individuals due to the combined effects of these two factors. The need for plastic also develops exponentially with the human population without consideration for what happens to it once it is consumed, discarded, or disposed of. Even though more people produce waste, the population is still growing. Despite their ease of disposal, the accumulation of disposable items like water bottles, soda cans, and plastic bags has resulted in a global rise in plastic pollution in the oceans [6].

In Sri Lanka, raw plastic is imported in 200,000 metric tons. Seventy percent of that enormous quantity has been used, and the remainder is being exported. In the western province alone, a staggering 3,500 metric tons of solid plastic waste is generated, highlighting the severity of the situation. However, the most concerning aspect is that only 2,400 metric tons are being collected. Out of the collected waste, only ten percent is recycled, leaving a significant 75 percent of the plastic waste being disposed of improperly [7]. Four hundred thousand thirty thousand tons of plastic are anticipated to be imported in the future prospectus about 2025, of which three hundred thousand ten thousand will be used. This is shown in Figure 1. Additionally, it is anticipated that 200,000 tons will be wasted [8].

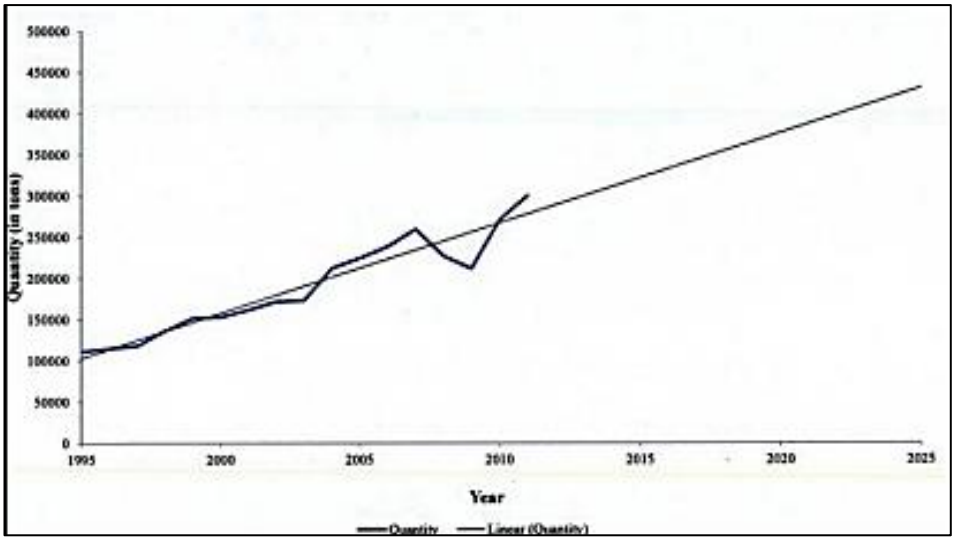


Figure 1: In Sri Lanka, there is an increase in the use of plastic

Source: [9]

In 1994 and 2006, the Sri Lankan government attempted to outlaw the use of polythene. However, it was unsuccessful because the public resisted it vigorously, and

the government needed to support its adoption strongly. In 2017, the government enacted legislation prohibiting polystyrene packaging, polyethylene sheets, and plastic incineration. Nevertheless, it has yet to be successful in that way. Except for these challenges, the Sri Lankan government successfully implemented rubbish separation, plastic separation, and polythene recycling as a first step in controlling marine debris [10].

The United Nations started a program named Environment's Cleanses. Their main objective is to clear the plastic waste gathered along the shore and recycle it [9].

The procedure of obtaining used or discarded plastics and reprocessing the material into useable products, usually in a completely different form from their original one, is called "plastic recycling" [11]. Classifying various plastic recycling methods based on the end product of any particular recovery process has allowed for more significant differentiation [12]. For example:

- Primary recycling: Products made from recycled plastic perform similarly to products made from virgin plastic. In a closed-loop recycling system, the recycled material is put back to use in the original application. Utilizing PET recovered from post-consumer bottles to create new bottles is an example of primary recycling.
- Secondary recycling: Compared to the original application, the recovered plastic products have lower performance requirements. Reformulation is frequently necessary for secondary recycling to meet the requirements of the new product. Making flooring tiles from mixed polyolefin is an example of secondary recycling.
- Tertiary recycling: In a process that yields chemicals and fuels, waste plastic is the feedstock. Tertiary recycling includes processes like the glycolysis of PET to create diols and dimethyl terephthalate, which can subsequently be utilized to create new PET.
- Quaternary recycling: Plastic garbage is burned to recover its energy. Quaternary recycling is shown by tire-derived fuels (TDF).

1.1.1 Recycling of waste thermoplastics

Thermoplastics

Thermoplastics are chemically processed after being generated in vast quantities from plants. Polyethylene, poly (vinyl chloride), polypropylene, and polystyrene are some of the most significant thermoplastics. Polyethylene includes high-density polyethylene (HDPE) and low-density polyethylene (LDPE). These polymers can be used for wire and other light-duty structural applications, among many others. Thermoplastic polymers are frequently used as matrix materials for synthetic and natural fibers [13]. Thermoplastic polymers have the characteristic of melting at specific temperatures, which allows them to be easily molded and remolded by reheating them to their melting point and then shaping them according to the desired mold. It is advisable to avoid recycling thermoplastics because doing so can cause the polymeric chains to break, causing the material to lose some of its physical qualities [14].

Recycling of waste thermoplastics

Processing tools including injection, film-blowing machines, single-screw extruders, processing parameters (temperature, material content, time, and rheological behavior), and product use, affect when waste thermoplastics are recycled [15]. The application of additives or modifiers, such as fillers, fibers, or compatibilizers (nonreactive and reactive), has been linked to easier processing and increased compatibility [16].

Even though recycled thermoplastics are less expensive than virgin ones, their subpar qualities [17], contaminations, and unsuitability [18] are still concerns for real-world applications. Compared to developing new polymers, blending technology is a feasible solution because of its low production costs, reduced technical risk, and eco-friendly materials [16].

Waste thermoplastics and natural materials can be used in thermoplastic modification techniques to produce composites with enhanced durability and characteristics [19],

[20]. Utilizing other waste thermoplastics is often considered economically unfeasible due to the expenses associated with blending and the incompatibility of different thermoplastics. Therefore, there is a need to develop a new compatibilizer that can facilitate the effective blending and compatibility of various waste thermoplastics, making their utilization more viable and cost-effective. Thermoplastic recycling is still dependent on using natural materials to transform used thermoplastics. Various factors primarily drive the alteration of plastic resins in industries. These include scientific research, the desire for innovation and development, economic optimization, and advancements in the properties of post-consumer plastic waste. This is because certain plastic products require specific processing and performance specifications that cannot be achieved with a single component alone. As a result, modifying plastic resins becomes essential to meet the desired requirements and improve the overall performance and functionality of the plastic product [21], [22].

Thermoplastic Composites

Short or long continuous fibers may be present in thermoplastic matrix composites. The two different forms of composites have quite different fabrication methods. Pellets are the primary raw material used to create short fiber-reinforced thermoplastic composites. The matrix material of these pellets contains short fibers. Short-fiber-reinforced thermoplastics have a far more comprehensive range of process parameters than plain thermoplastics, including heat conductivity, tool wear, rheological characteristics, and shrinkage characteristics [23] [24].

The blank is heated before being promptly transported to a press that has a die in the form that is wanted. It is then subjected to pressure and maintained until it cools down [25]. This method utilizes pressure and heat to mold the flat sheet into the appropriate shape. This technique can be divided into two categories: diaphragm forming and hydroforming, depending on how pressure is applied.

Similar to filament winding, tape winding involves wrapping thermoplastic prepregs tape around a mandrel. When the roller and mandrel come into contact during the

process, pressure and heat are applied. This method eliminates the curing stage necessary for thermosets by combining melting and consolidation in a single step.

The most efficient form of close molding, compression molding, is used to create the item into the die cavity. The molding charge in the die can be made of bulk molding compound or sheet molding compound. For this procedure, either hot pressing or cold pressing can be used. This procedure has a long curing time but provides dimensional accuracy and a good surface finish [24].

Injection molding, using either a screw-driven or plunger-driven mechanism, is the most popular technique for producing thermoplastic matrix composites reinforced with short fibers. The process of injecting, forcing, or shoving a fluid material into a sealed mold is called "injection molding" [26]. The hopper is used to supply the molding compound into the injection chamber during the injection molding process. The material undergoes heating within the injection chamber, transforming into a liquid form. The plunger forces it through the nozzle and into the mold. In general, injection molding allows for finer part details than compression molding, which is easily automatable [27].

In the quest for alternatives to pellets, which are fiber-resin mixtures produced through twin-screw extrusion, dry blends containing the polymer matrix and short fibers have been investigated for injection molding machines. However, it has been observed that parts created using this approach display slightly different strengths and rougher surface texture due to the uneven distribution of the fibers inside the matrix.

It is frequently possible to design the item and mold so that no additional trimming or machining steps are necessary. This approach is typically used to develop and mass-produce inexpensive components. One of its drawbacks is the method's limitation on extremely short fiber lengths and small fiber volumes. Furthermore, the operation involves a lot of material flow, which could injure the fibers of the barrel.

1.1.2 Composites made of natural fiber-reinforced polymers (Thermoplastic composites)

The use of natural fiber-reinforced polymer composites is expanding in fundamental and real-world studies and industry. They are cheap, biodegradable, entirely or partially recyclable, renewable, and renewable. Throughout history, plants such as flax, ramie, cotton, jute, hemp, sisal, pineapple, bamboo, kenaf, banana, and wood have been widely used as a source of lignocellulosic fibers. Utilizing these plant fibers as reinforcements in composite products has become more popular recently. These natural fibers provide an environmentally beneficial alternative to the common usage of glass, carbon, and synthetic fibers in composite materials. The appeal of these lignocellulosic fibers lies in their abundance, renewability, affordability, and acceptable mechanical properties. They are readily available and can be sourced sustainably, reducing the dependence on non-renewable resources. Additionally, the cost-effectiveness of these natural fibers makes them an attractive choice for composite manufacturing. Although natural fibers may not possess the same mechanical properties as glass, carbon, or synthetic fibers, they exhibit satisfactory performance characteristics for many applications. When properly processed and integrated into composite materials, these natural fibers can provide sufficient strength, stiffness, and durability [28].

Natural fiber-containing composites are widely used in various industries for their eco-friendly, sustainable, and durable properties. They are used in packaging, consumer goods, military, building, construction, and transportation. In packaging, they create biodegradable materials like trays, containers, and cartons, while in consumer goods, they balance aesthetic appeal, performance, and sustainability. They offer acoustic and thermal insulation properties in construction, contributing to sustainable building practices. In transportation, they improve weight reduction, fuel efficiency, and sustainability by incorporating natural fiber composites into vehicle components [28].

1.1.3 Kithul fiber as a natural fiber in natural fiber polymer composites

Kithul (Caryota urens) is innate to Sri Lanka, Malaysia, and India and goes under several names, including sopari (Bengali); fishtail palm, kithul palm, Indian sago palm,

toddy palm, wine palmjaggery palm, (English); dirgha, mada (Sanskrit); mari (Hindi); kithul (Sinhala); and koondalpanai, kundal panai, thippali, konda panna, tippili (Tamil) [29].

Kithul palms are said to be prevalent in Sri Lanka's mid and low country interior up to 1,500 m, with an altitude limit of 1200 m for their ecological range. Palm trees are mainly found in the natural forests of the lowlands.

A range of goods, including vinegar, treacle, toddy, and jaggery, are produced using the kithul inflorescence, which is typically tapped for its sap [30]. According to the published data, palm generates 24 tons/hectare per year instead of rice's 6 tons/hectare, and crops like wheat and potatoes' 5.5 tons/hectare and 2.5 tons/hectare, respectively. The pith, used to make flour, is produced by the trunk in quantities of 100 to 150 kg per palm [29].

Perera et al., 2019 characterized the kithul fiber to evaluate the properties of length, diameter, breaking force, tenacity, elongation, and moisture content of kithul palm fibers. The research study was accomplished, and the length and diameter were 65cm and 0.85mm, respectively. Breaking force, tenacity, and elongation values were shown as 35.67N, 10.26cn/tex, and 45.20% correspondingly. Conferring to the research paper, 14% of the moisture content value was attained in kithul palm fiber [31].

This study examined the physical and mechanical characteristics of a few different natural fibers. These characteristics included average diameter, fiber density, water absorption, and tensile strength. Then, a composite material was created using waste polyethylene as a matrix material and kithul fiber as reinforcement. This research also discusses this composite material's tensile and bending properties at various stages of composite development (changing the ratio, processing temperature and pressure, and kithul fiber length). The composite material was finally created after the chosen ratio, temperature, pressure, and fiber length. The properties of the produced composite material were then evaluated using tests for impact strength, thickness swelling, water absorption, and flammability. Finally, it was established that this material will be

employed as a natural fiber composite material in several industries, including building construction.

1.2 Aims and Objectives

- To determine the physical and mechanical properties of selected natural fibers and the selected waste polyethylene.
- To develop a composite material with the Kithul fiber with waste polythene with varying the fiber weight fraction, composites processing temperature and pressure, and fiber length.
- Testing and evaluation methods are employed to ascertain the resulting composite material's physical and mechanical characteristics.

1.3 Scope

The investigation into the advancement of kithul fiber-reinforced polymer composites using waste polyethylene can cover the following areas of study:

- Fiber Properties: Characterize the kithul fibers to determine their mechanical, physical, and chemical properties. Investigate the fiber diameter, density, water absorption, SEM analysis, tensile strength, and FTIR test to understand their potential as reinforcement in polymer composites.
- Waste Polyethylene Properties: Evaluate the chemical properties of waste polyethylene, to verify the selected polyethylene type.
- Composite Development: By changing the ratio of fiber to matrix, processing pressure, and temperature, as well as fiber length, investigate the creation of kithul fiber-reinforced polymer composites. Investigate the impact of these factors on the composite material's process ability and mechanical properties.
- Composite Board Production: Produce composite boards using the optimized parameters determined in the previous scope. Utilize the compression molding technique, to fabricate the boards. Ensure consistent distribution of fibers throughout the material and establish strong bonding between the fibers and matrix to achieve a uniform and well-connected structure.

- Impact Resistance: Using standardized impact tests, determine the impact resistance of the generated composite boards. Evaluate the composites made using kithul fibers for their impact resistance. Compare the impact resistance of the kithul fiber composites with that of other materials already in use to determine their suitability for applications requiring impact resistance.
- Water Absorption and Thickness Swelling: Assess the water absorption performance of the composite boards by submerging them in water and monitoring the increase in weight over a specific period. Assess the impact of water absorption on the dimensional stability and mechanical properties of the composites. Additionally, measure the thickness swelling of the boards after immersion to evaluate their resistance to moisture uptake.
- Flammability Analysis: Examine the flammability properties of composites made from kithul fibers and polymers. Conduct horizontal flammability tests, to assess their fire resistance and compare them with relevant industry standards.

1.4 Thesis Outline

Following are the seven chapters that constitute the thesis:

CHAPTER – 1 presents the background of the research study, its aims, objectives, scope, thesis outline, and the Gantt chart.

CHAPTER – 2 presents an overview of the composite material and its phases - reinforcement and matrix - in the section labeled "Review of Literature," along with information on the review of materials, historical development, applications, and uses of composites. The production procedures for creating polymer-based composites and their prospects and difficulties have been outlined.

CHAPTER – 3 addresses the raw materials employed, the preprocessing method, the evaluation of the raw materials' attributes, and the production steps involved in sample preparation.

CHAPTER – 4 describes the experimental findings of the physical, mechanical, and chemical-physical characteristics of the chosen natural fibers and waste polyethylene. Additionally, it defines the created composite material's mechanical and physical characteristics.

CHAPTER – 5 is entitled to the contribution and results of this study along with the potential for further investigation.

CHAPTER 2

2.1 Literature Review

2.1.1 Chapter Introduction

The chapter provides readers with a background of composite materials and an overview of composites, matrixes, and natural fibers. In this part, earlier research on polymer-reinforced natural fibers was reviewed. Its goal is to gather essential information about the field of study to provide more ideas and identify research gaps before implementing the project. Most of the sources used to compile this information are textbooks and journals.

2.1.2 History of composite materials

For hundreds of years, people have used composite materials. At that time, they created bricks out of mud using technology that dates back a thousand years. In 1500 B.C., the composite word was first used. Mud and straw were combined to create strong and long-lasting structures in early Egyptian and Mesopotamian artisans and builders. Straw was used as reinforcement in the production of ancient composite products, including pottery and boats. Then, ten books on architecture were published in 25 B.C. that explained the concrete structure and different kinds of lime and mortars. Engineers, builders, artisans, and manufacturers have been attempting to develop the utilization of composite materials in various fields in a more sophisticated manner since ancient times. The first composite bows were created by the Mongols in 1200 AD. They were made from bamboo, wood, horns, cattle tendons, and silk and were the most potent and precise weapons until the 14th century [32]. Between 1870 and 1890, the advancement of composite materials experienced a transition due to the chemical revolution. Instead of utilizing celluloid, melamine, and Bakelite, new synthetic polymers emerged, and the polymerization technique has transformed these polymers from a liquid to a solid state. Before focusing on creating plastics, scientists in the modern era still needed to start to build composite materials. Plastic materials, including vinyl, polyester, polystyrene, and phenolic, were reinforced and developed during the beginning of the 20th century. Bakelite, the first resin, was developed using

synthetic materials in 1907. Compared to other composite materials, these novel synthetic materials offered superior performance. Plastic by itself, however, cannot offer enough strength and rigidity for structural uses. Therefore, adding more reinforcement to the structure is crucial to improve its power and rigidity [33]. The fiber-reinforced polymer (FRP) industry was first presented by Owens Corning in 1935, along with the first announcement of glass fiber. As we know, resin development began in the 1930s, with methods and techniques still employed in the composites sector today. Fiberglass and plastic material combined create a solid structure. It was invented in 1936 to create unsaturated polyester resins (UPR). In 1938, other better-performing resin systems were used [34].

2.1.3 Overview of composites

A composite material has chemically distinct phases and tiny layers of two or more constituents. As a result, a composite material is statistically homogenous at a macroscopic size yet heterogeneous at a microscopic scale [35]. A metal or alloy that contains impurities and a composite are distinct from one another. In contrast to alloys, where it is impossible to identify the separate constituents from the cross-section physically, composites allow for the physical identification of both the component and the interface [36]. According to the specifications stated in ASTM D3878, a composite is described as a singular material comprising two or more insoluble components that collectively yield an engineering material possessing distinct characteristics that are difficult to achieve individually [37]. The following conditions must be met to be classified as a composite material.

- It is manufactured except for natural composites.
- Significant property changes should occur when materials are combined, especially if one form is fibrous.
- The components often make up more than 10% of the total volume.
- It is composed of two or more scattered phases that are physically and chemically distinct.
- Generally, a constituent's property should be greater than the comparable property of other constituents.

Composites can be created using both natural and synthetic materials. Wood, graphite, bone, and other naturally occurring materials are examples of composites, but concrete and plywood are manufactured materials. The bones and muscles of the human body are a prime illustration of the natural composite. The bones contain mineral matrix material that holds the muscle fibers together in a layered system of fibers with various orientations. Further examples are a fish's fin, a bird's wing, a tree leaf, and grass. In addition to these, concrete, which is composed of sand, gravel, and cement and is used with steel in building applications, is the application that occurs most frequently in daily life [35], [38]. Constituent materials are another name for the ingredients that make up a composite. The majority of composites consist of two primary stages. The first stage, the continuous phase or matrix, comprises metals, polymers, or ceramics. Embedded within this matrix is the second stage, referred to as reinforcement, which includes fibers, particles, flakes, or fillers. The interface is the area between the continuous and scattered phases [37]. Composite materials can be categorized generally based on these stages (Figure 2 and Figure 3). The fibers and the matrix in composites keep their physical and chemical identities, but their combined use yields various benefits that neither component could create alone. The primary objective of this material is to create a balance of attributes by combining various elements. Coupling agents, coatings, and fillers are other elements that can be used. By enhancing the wetting of the fibers with the matrix material, the addition of coupling agents and coatings on the fibers improves the bonding between the fibers and the matrix [39].

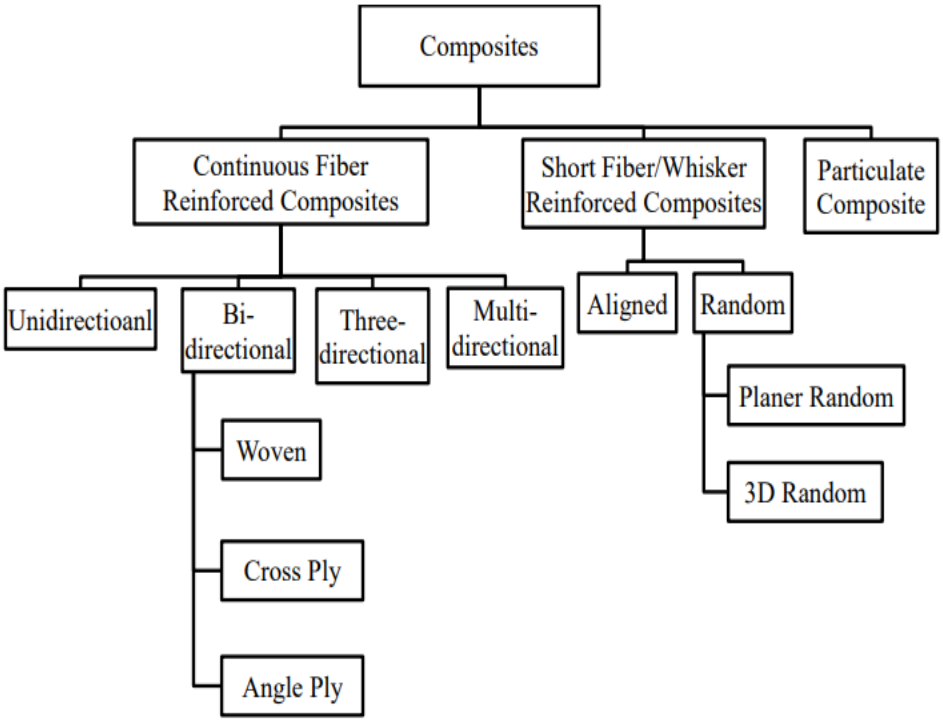


Figure 2: Classification of reinforcement composites using the dispersed phase
Source: [39]

Synthetic fiber production predominated for a long time; nevertheless, industrial uses have sprung up in recent years in response to the growing interest in environmental consciousness. Natural fiber stands out as reinforcement above traditional synthetic fiber for engineering applications due to its availability, low density, low weight, high strength, meager cost, and biodegradable nature. The growing awareness of social and environmental issues has increased demand for environmentally friendly plastics as a substitute for traditional plastics. A green composite (G.C.) can be generated when a biopolymer and natural fibers are combined. These days, packaging industries and other low-strength applications employ this composite type [40] [41].

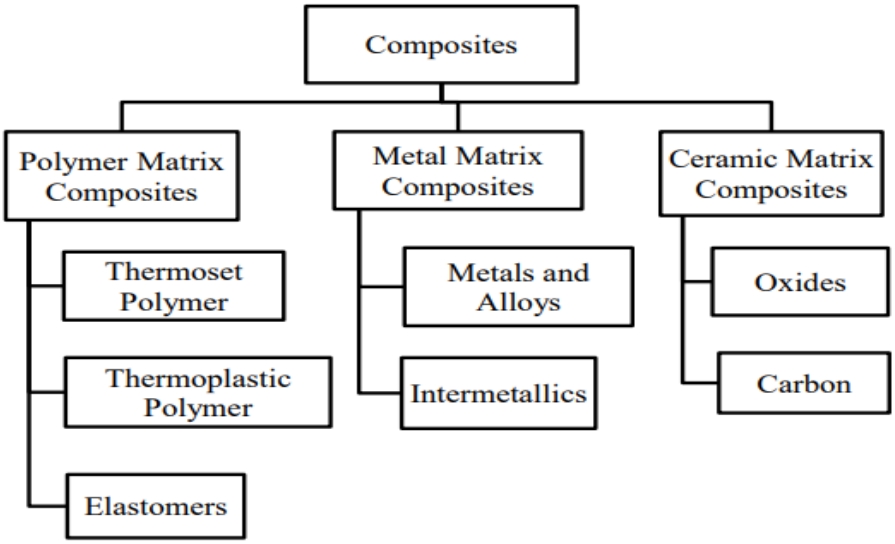


Figure 3: Matrix-based composite classification

Source: [41]

Green Composites have recently seen significant interest due to the demand for affordable building materials, increased fuel efficiency in automobiles, and raised awareness of the environment among people worldwide. Natural fiber-reinforced composites have become a compelling alternative to glass and carbon fiber-reinforced composites in the construction and automotive sectors, primarily due to their weight reduction and cost-effectiveness. Fibers are utilized as high-performance engineering materials owing to their small microstructural unit size, high aspect ratio, and impressive flexibility. The benefits of using natural fibers in composites for different purposes can be summed up: they have strong thermal and acoustic insulating qualities, are simple to produce, have a low specific weight, and do not damage machinery [42].

Nevertheless, drawbacks such as poor moisture resistance significantly diminish the potential of natural fibers. In addition to the restricted maximum processing temperature, industrial applications of natural fibers may be constrained by reduced durability and price fluctuations.

2.1.4 Natural fiber

A "natural fiber" refers to any raw material resembling hair and can be obtained directly from sources such as plants, animals, or minerals without extensive processing. When spun into threads, it may produce non-woven materials like felt or paper and woven fabrics. Natural fiber can also be understood as a group of cells with a relatively small diameter compared to their length. Although fibrous materials are abundant, particularly those derived from cellulose sources like cotton, grains, wood, and straw, only a few are suitable for manufacturing textiles or other industrial products. The length, strength, pliability, elasticity, abrasion resistance, absorbency, and a variety of fiber surface properties also impact its economic feasibility. Many of the fibers used in textiles are thin, flexible, and reasonably strong. Since they can partially or entirely recover to their original length after stretching, they are elastic [43].

2.1.5 Classification and Properties of natural fibers

The origin of a natural fiber can be used to classify it. Jute, flax, and cotton are crucial cellulose-based plant fibers (Figure 4). Examples of animal-based or protein-based fibers include silk, mohair, and wool. The mineral family contains a large fiber called asbestos.

The origin of the vegetable fibers within the plant allows for the division of the fibers into smaller groupings. Cotton, kapok, and coir are fibers that initially originate as hair-like structures on fruit seeds or inner walls. These fibers are each composed of a single, long, thin cell. Flax, jute, hemp, and ramie are bast fibers composed of overlapping cells in the inner bast tissue of particular plant stems. The leaves of abaca, henequen, and sisal fibers are in their fibrovascular system. Chemically, cellulose makes up the majority of all vegetable fibers. However, they also include various levels of hemicellulose, lignin, pectin, and waxes, all of which must be eliminated or decreased during processing [44].

Except for silk, animal fibers consist entirely of proteins and function as the protective outer covering of animals. Moth larvae produce silk threads that they utilize to spin their cocoons [45].

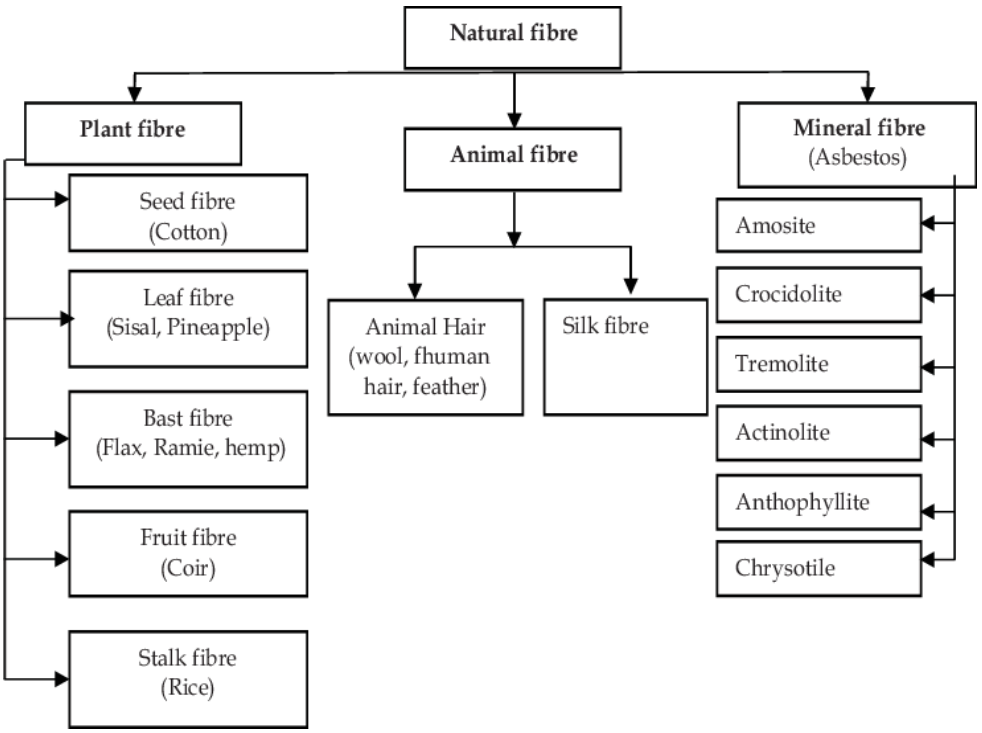


Figure 4: The categorization of natural fibers

Source: [44]

Except for mineral fibers, natural fibers demonstrate an attraction to water in both its liquid and vapor forms. This strong attraction leads to fiber swelling upon water absorption, which aids in the dyeing process under wet conditions [44] [46] [43].

Most natural fibers are called lignocelluloses because they are spirally coiled cellulose microfibrils enclosed in a matrix of lignin and hemicellulose [47]. Natural fiber composite matrices have many advantages over an unreinforced matrix since the resulting composites are more robust and durable. Natural fibers made of cellulose are also widely available, robust, lightweight, reasonably priced, and renewable. Natural lignocellulosic fibers, like those in pineapple leaves, provide an inexpensive and abundant substitute for costly and nonrenewable manufactured fiber [48]. The mechanical properties of the polymer matrix are improved by incorporating these fibers with high specific strengths. Fibrous plants are common in tropical areas like Malaysia, where some types are grown as crops. The size, form, and orientation of the

single fiber, the crystallite composition of the crystallite, and the cell wall's thickness all affect its properties. This unique structure is there, as evidenced by the fibers' stress-strain graphs. Table 1 indicates the mechanical properties of natural fibers.

Table 1: Characteristics of synthetic and natural fibers

Type of fiber	Density g/cm3	Tensile Strength MPa	Young's Modulus GPs	Elongation at beark %
Cotton	1.5-1.6	287-800	5.5-12.6	7.0-8.0
Jute	1.3-1.45	393-773	13-26.5	1.16-1.5
Flax	1.50	345-1100	27.6	2.7-3.2
Hemp	-	690	-	1.6
Sisal	1.45	468-640	9.4-22.0	3-7
Kenaf	1.4	930	53	1.6
Pineapple	-	413-1627	34.5-82.51	1.6
Coir	1.15	131-175	4-6	15-40
E-glass	2.5	2000-3500	70	2.5
Carbon	1.7	4000	230-240	1.4-1.8

Source: [49]

2.1.6 Natural fiber as a fiber reinforcement in composite

Many production sectors are giving more attention to how natural fibers are used in industry. Natural fibers are experiencing growing utilization in polymer composites for diverse applications across industries such as building, transportation, and low-cost construction [50]. Various factors, including the type of plant, growing conditions, soil quality, temperature, and humidity levels, significantly impact the properties of natural fibers. Natural fibers find applications in multiple sectors, such as the automotive industry, non-structural composites, packaging, geotextiles, sorbents, molded products, filters, and composite materials. Structural beams and panels have been created, produced, and examined by employing natural fibers and plant oil-based resins [51]. Compared to pure polylactic acid, kenaf and hemp fiber bundles and their combinations significantly increase the composite's tensile strength and Young's modulus while lowering its impact strength. The components made with these

composites must have low impact stress and excellent tensile strength. Instances comprise furniture, panels, and mounts for abrasive discs. Contrarily, cotton fibers produce a material that is stiffer and has a lower tensile strength, but it has a high impact strength. These composite materials may be utilized for impact-resistant components, such as the interiors of automobiles or helmets. Combining bast and cotton might provide composite materials with high impact and tensile capabilities, making them appropriate for bags and other automobile parts [52]. The automotive industry has successfully shifted from utilizing materials such as glass mat PMC or polymeric foams for components like interior panels and seat cushions to adopting composites that incorporate diverse types of natural fibers as reinforcements [53]. Silk sutures are a popular surgical tool due to their biocompatibility, biodegradability, and strength. They offer excellent handling properties and minimize tissue trauma during wound closure. Silk can also be processed into films, fibers, and scaffolds for biomedical applications. In orthopedics, silk-based composites can be used for bone graft substitutes, implant coatings, and tissue engineering scaffolds. In bioengineering, silk-based composites offer promise for tissue engineering and regenerative medicine, promoting tissue regeneration. Using animal-based fibers, particularly silk, in developing biodegradable, biomedical, and bio-resorbable composite materials demonstrates their potential in advancing orthopedic and bioengineering fields [54].

Numerous manufacturing sectors are paying increasing attention to natural fiber industrial applications. The construction, transportation, and low-cost building sectors are witnessing a growing trend in utilizing natural fibers in polymer composites, driven by the need to achieve diverse end applications [50]. Plant type, growing conditions, soil quality, temperature, humidity, and humidity greatly influence natural fiber properties. Natural fibers offer advantages across multiple industries, such as automotive, non-structural composites, molded goods, packaging, sorbents, filters, geotextiles, and material combinations. Notably, bio-based composite materials incorporating plant oil-based resins and natural fibers were employed in designing, manufacturing, and assessing structural beams and panels [51]. Combining natural fibers with polylactic acid (PLA) can create composite materials with tailored mechanical properties for specific applications. Kenaf and hemp fiber bundles enhance

tensile strength and Young's modulus, making them suitable for furniture, boarding, and grinding disc holders. Cotton fibers demonstrate notable impact strength while displaying relatively lower tensile strength and stiffness levels. This combination of properties makes them well-suited for applications in impact-stressed components such as safety helmets and automotive interiors. By harnessing these characteristics, natural fiber-reinforced composites can be tailored for diverse industries and applications [52]. The automotive industry progressively embraces composites that integrate various natural fibers as a successful substitute for interior panels and seat cushions, traditionally composed of glass mat PMC or polymeric foams [53]. For orthopedic and bioengineering applications, composite materials from animal and plant fibers can be biodegradable, biomedical, and bio-resorbable. There have been biological uses for silk stitches [54]. Table 2 depicts the products and applications of natural fibers.

Table 2: Products and applications of natural fibers

Natural fiber	**Product**	**Application**	**Reference**
Coir	Concrete with coir fiber reinforcement	Construction materials used in civil engineering	[55]
Banana stem	Composite pipe made of PVC and banana stems	Industries related to energy	[56]
Coir	Panels, insulators, lightweight alternative building materials, engine guards, and wall panels made of coir polyester composite.	Industries relating to automobiles, constructing materials, and electricity.	[57]
Banana, pineapple leaf fiber	Composite made of banana and pineapple leaf fibers	Building materials, electronic components, and interior auto parts	[58]

Banana	Mat and yarn	Automobile and aerospace components	[59]
Sugarcane fiber	Increase the strength of conventional concrete with concrete blocks	Materials used in building construction	[60]
Coconut coir, bagasse fiber	The panel made of composite material	Interior of an automobile, wall ceiling	[61]
Banana fiber	Agriculture waste and local plastic are used to make composite panels	Materials for construction	[62]
Coir	Fiberboards	Furniture and construction industries.	[63]
Coir	Concrete reinforced with coir	Roads, bridge decks, and buildings	[64]
Hemp	Board for thermal insulation	Construction and public works sectors	[65]

2.1.7 Manufacturing of Polymer Composites

The specific type of matrix utilized and the structure of the material influence the procedure to create composites. Figure 4 depicts an overview of fabrication procedures for all composite materials. A material is considered a metal matrix composite (MMC) if it consists of at least two components, one of which is metal and the other of which may be ceramic or an organic compound [66]. MMC's matrix material can be made of steel, magnesium, titanium, copper, or aluminum. In contrast, the reinforcement materials Alumina, Silicon Carbide, Titanium Nitride, and Zirconium can be used as particles, whiskers, long fibers, or sheets of laminates, respectively [67]. The production technique for MMC is determined by the amount and distribution of both phases and their planned uses [68]. To improve the properties that monolithic ceramic materials lack, one or more different ceramic phases are intentionally combined with another material to form ceramic matrix composites (CMC) [66]. In CMC, ceramic materials can be reinforced with continuous or discontinuous reinforcement, like fibers that have been chopped, whiskered, or incorporated into other materials [69]. Carbon, glass, oxides, etc.; are the primary reinforcement materials used in ceramic matrices [70].

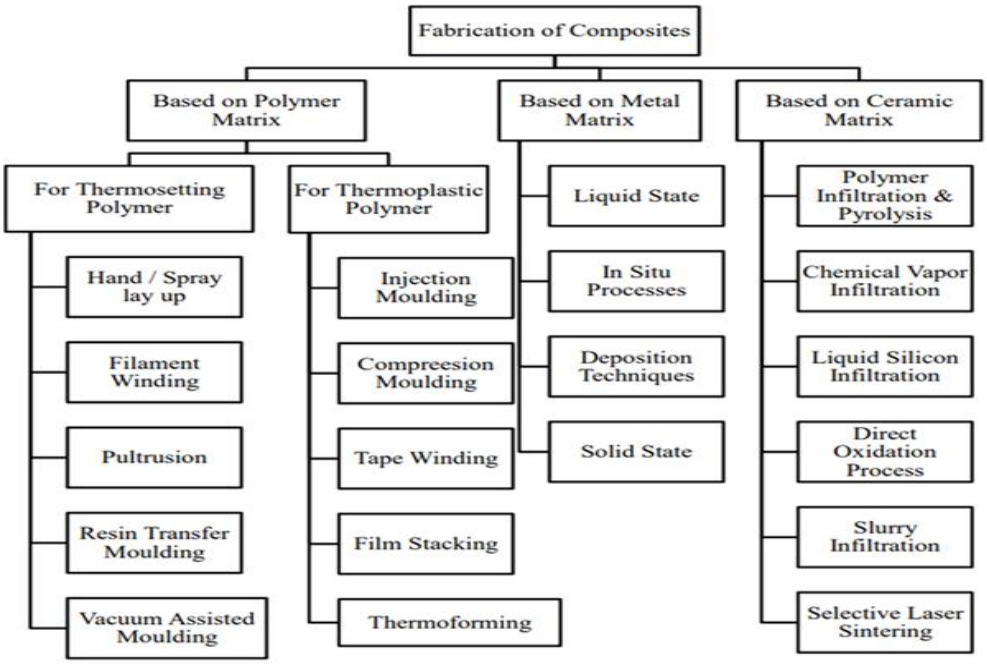


Figure 5: Different fabrication processes of composites

Source: [66], [69]

2.1.8 Matrix material

Matrix materials encompass various compositions, from polymers to metals to ceramics. The matrix enables surface connection to hold the reinforcing pieces together. Additionally, a matrix is a substance that provides a composite of its body and binds the reinforcement together, often having a lesser strength than the reinforcement. Although the plastic matrix is weak and flexible, it has a low density. Even though the fibrous reinforcement may be powerful and rigid, it still requires a support structure to distribute weight properly and protect the fibers from damage. While remaining light, robust, and durable, the combination may compensate for the limitations of its elements. By altering the choice of components, proportions, and shapes, it is possible to generate a diverse range of engineering properties for a component. These properties can exhibit various physical characteristics at different levels of measurement [71]. Additionally, serving as a binder to preserve the reinforcing components together is the matrix. Furthermore, the matrix degrades when a composite is stressed, and the external force is distributed uniformly among the fibers. The matrix material plays a crucial role in resistance to fracture propagation and enhancing damage tolerance in a component. This is achieved through plastic flow at locations where damage has occurred. The matrix, which typically surrounds and supports the reinforcing fibers or particles in a composite material, can deform plastically when subjected to external forces. This plastic flow helps to absorb and redistribute stress, preventing the propagation of fractures and increasing the component's overall damage tolerance. By enabling localized plastic deformation, the matrix material contributes to the structural integrity and durability of the composite, making it more resistant to failure. The matrix is crucial when handling composite materials since it protects the fibers' surface from abrasion and other adverse environmental consequences [72]. The matrix also roughly evenly distributes the loads among the fibers, stops fractures from spreading and causing damage, and prepares the composite's entire interlaminar shear strength while ensuring that the reinforcing fibers remain in the proper orientation and position to support the necessary loads. The matrix also typically determines the composite's maximum service temperatures and regulates its resistance to the environment [71]. To produce a strong and rigid solid basis for

engineering applications, such strong fibers are needed and employed to embed the matrix. Typically, the characteristics of the matrix material are selected to complement those of the fibers in a composite. For instance, a matrix possessing exceptional toughness has the potential to augment the tensile strength of the fibers. By carefully choosing the matrix-fiber combination, a composite material can achieve a high level of strength and stiffness. This is primarily accomplished through carefully choosing the matrix-fiber combination, a composite material can achieve high strength and stiffness. This is primarily accomplished through the fracture propagation resistance offered by the fibers, the interaction between the fibers and the matrix, and several other factors that collectively contribute to the overall performance of the composite. Combined with these characteristics, the result is a composite material with improved mechanical properties, including increased strength and stiffness. Thermoplastics and thermosets are the two primary categories into which matrices are often categorized. Only the composite end-use requirements affect the selection criteria of the matrices. For example, when a composite material needs both improved temperature tolerance and chemical resistance, thermoset matrices are preferred over thermoplastic matrices. When there is a need for a composite material that exhibits high damage tolerance and can be easily recycled, thermoplastics are suggested as a viable alternative [73].

2.1.9 Thermoset

Wet-forming techniques or methods utilizing premixes or prepregs create thermoset composites. Liquid resin is used to produce the finished product during wet forming operations. Introducing external heat and pressure may help the resin cure in the final product [74]. Other processes that use premix/prepregs forms—prefabricated materials such as bulk molding compounds and semi-cured sheet molding compounds—provide the shape of the final product [75]. An open mold procedure known as "hand layup" or "spray layup" entails manually applying resin and fibers (often glass fibers) using hand instruments that come into contact with the environment [69]. It is a relatively inexpensive production technique with no restrictions on the product size, but it cannot manufacture parts with a decent surface polish [38]. Long continuous fibers that have been resin-impregnated are wrapped around a revolving mandrel at the desired

location and angle in the winding process. The positively curved surface is created using it [69]. Pultrusion is a continuous production method that produces parts with a continuous cross-section by pulling resin-impregnated long fibers through a die, similar to the extrusion process [67]. Although this technology enables the production of significant components with thin walls, ensuring precise tolerances can be challenging. Resin transfer molding (RTM) involves arranging fibers in a desired geometric pattern within a tightly fitted mold cavity. A low-viscosity resin, commonly polyester or epoxy, is injected under pressure into the cavity, thoroughly impregnating the fibers before curing [69], [76]. Compared to the manual layup procedure, this method produces more material faster. In the vacuum-assisted method (VAM), the resin wets the fiber with the help of a vacuum because the resin passes into the fiber without trapping air, minimizing defects like porosity [67]. Impregnation, injection molding, or a subpar molding technique can all help this process. Vacuum bag molding is closed before the autoclave and cures materials under high pressure and temperature [76].

2.1.10 Thermoplastic

Short or long continuous fibers may be present in thermoplastic matrix composites. The two distinct forms of composites have quite different fabrication methods. Pellets serve as the primary fundamental component of short fiber-reinforced thermoplastic composites. The matrix material of these pellets contains short fibers. Short-fiber-reinforced thermoplastics have a far more comprehensive range of process parameters than plain thermoplastics, including heat conductivity, tool wear, rheological qualities, and shrinkage characteristics [76]. The thermoforming technique involves heating the blank, which is then swiftly transported to a press equipped with a die of the desired shape and kept under pressure until cooling [67]. This method utilizes pressure and heat to mold the flat sheet into the appropriate shape. This procedure can be categorized as either hydroforming or diaphragm forming, depending on the method employed to apply pressure. Similar to filament winding, tape winding involves wrapping thermoplastic prepregs tape around a mandrel. Pressure and heat are applied at the interface between the roller and mandrel [67]. Integrating the melting and

consolidation processes into a single step eliminates the need for the curing stage typically required for thermosets. Compression molding is the quickest method for closely molding an item into a die cavity. It is possible to use bulk or sheet molding compound as the molding charge is inserted into the die [76]. Either hot pressing or cold pressing can be utilized for this technique. This procedure has a long curing time but provides dimensional precision and excellent surface polish [67]. The ideal method for producing thermoplastic matrix composites with short fiber reinforcement is injection molding, which uses plungers or screws. A fluid substance is forced, pushed, or injected into a closed mold during injection molding [66], [76]. Using the hopper, the injection chamber is fed with the molding compound. In the injection chamber, the substance is heated, causing it to become liquid. The plunger forces it through the nozzle and into the mold. In general, injection molding allows for finer component details than compression molding, which is also easily automatable [77]. The use of pellets, premixes of fibers, and resin created through melt-processed twin-screw extrusion has been tested to be replaced with dry blends of the polymer matrix and short fibers. The uneven distribution of fibers in the matrix causes the items using this approach to have somewhat variable strength and rougher surface quality. It is frequently possible to design the item and mold so that no additional trimming or machining steps are necessary. This approach is typically used to develop and mass-manufacture inexpensive components. The method's limitation is that it can only be used with fibers with extremely short lengths and a small volume. Furthermore, the operation involves a lot of material movement, which might harm the fibers inside the barrel.

HDPE

A polymer with a liner structure and few short branches, HDPE has a density of 0.941-0.965 g/cm3, a melting point of 120-140°C, a producing temperature of 180-230°C, and is high tensile strength, excellent chemical resistance, low water absorption, outstanding electrical insulating characteristics, and simplicity of processing. HDPE is primarily used to make packaging bottles, ice boxes, pipes, ropes, and other items because it has better mechanical and thermal properties than LDPE but less hardness,

flexibility, and scalability [78], [79]. The properties of High-Density Polyethylene are presented in Table 3.

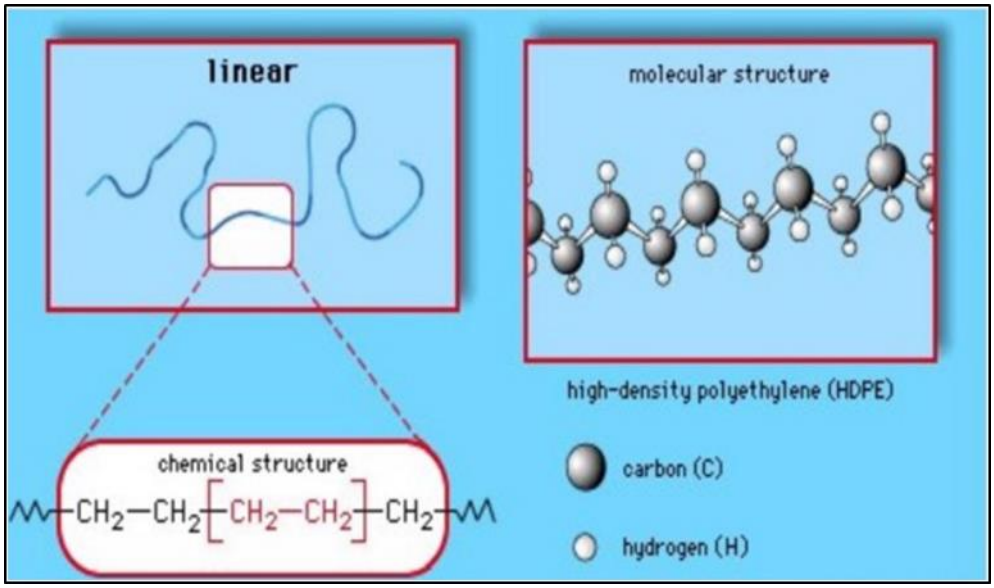


Figure 6: HDPE profile

Source: [80]

Table 3: Properties of High-Density Polyethylene

HDPE	Extrusion	Injection Molded
Physicsl Properites		
Density	0.96g/cm³	0.96g/cm³
Water Absorption, 24hrs	0.016%	0.016%
Mechanical Properies		
Tensile Strength	26.1MPa	26.1MPa
Tensile Modulus	0.966GPa	0.966GPa
Tensile elogation at Break	560%	560%
Flexural Strength	29.2MPa	29.2MPa
Flexural Modulus	1.10GPa	1.10GPa
Compressive strength	12.6Mpa	12.6Mpa
Hardness (Rockwell R)	48.7	48.7
Thermal Properties		
Coefficient of Linear Thermal Expansion	143 µm/m-°C	143 µm/m-°C
Heat Deflection Temperature (0.46MPa)	72.3 °C	72.3 °C
Max Operating Temperature (Air)	96.8 °C	96.8 °C
Thermal Conductivity	0.396 W/m-K	0.396 W/m-K
Glass transition Temperature	115 °C	115 °C
Vicat Softening Temperature	119 °C	119 °C
Rheological Property		
Melt Flow Index	25.7g/10minutes	25.7g/10minutes
Processing Properties		
Processing Temperature	211°C	211°C
Melt Temperature	212°C	222°C
Adapter Temperature	247°C	/
Die Temperature	235°C	/
Head Temperature	212°C	/
Nozzle Temperature	/	241°C
Mold Temperature	/	29.4°C
Drying Temperature	/	59.3°C
Injection Pressure	/	56.2MPa

Source: [80]

2.1.11 Properties of natural fiber composites

Due to their widespread availability, cost-effectiveness, lighter weight, low manufacturing costs, and reasonably favorable physical and mechanical properties like tensile strength, tensile modulus, and flexural strength, natural fibers are progressively favored over synthetic fibers. Moreover, natural fibers possess biodegradable and environmentally friendly characteristics, increasing their popularity. Natural fibers have been grown and used to produce non-structural items like bags, brooms, fishnets, and filters, particularly in rural developing nations. Natural fibers can also be utilized as insulation for walls and roofing. When examining the attributes of natural fiber, a notable distinction exists [81]. Natural fiber-reinforced composites' mechanical properties vary depending on parameters such as fiber type, surface chemistry, moisture content, shape, presence of other elements, and fiber-matrix interface quality. Specific needs like tensile strength, modulus, and elongation at break determine the fiber type used. The adhesion between fibers and the matrix can be improved by applying surface treatments like chemical, plasma, or coupling agents. Moisture content and form also affect composite properties, with long fibers providing better reinforcement and short fibers or fabric forms offering better processability. Combinations of natural fibers with other compositions, such as epoxy resin, can affect the composite's mechanical behavior. The interface between the fiber and matrix is essential to ensure efficient stress transfer and uniform load distribution. Factors like cultivation practices, growth duration, harvesting methods, extraction, retting, isolation, and processing techniques also affect the properties of natural fibers. Optimizing the selection, treatment, and processing of natural fibers can help achieve desired mechanical properties, tailoring performance to meet specific application requirements and ensuring a balance between strength, stiffness, impact resistance, and other attributes [82], [81]. Numerous studies have been conducted to evaluate the effects of fiber types and processing methods on the density, elongation at break, Young's modulus, and tensile strength of composites reinforced with natural fibers. Natural fibers have better mechanical properties, more outstanding durability, and higher modulus than synthetic fibers. Bamboo, flax, ramie, abaca, hemp, kenaf, jute, sisal, and bagasse are some of these fibers [83], [84]. Table 4 provides a compilation

of the most commonly used natural fibers and synthetic fibers, along with their corresponding mechanical properties.

Table 4: Mechanical characteristics of natural and synthetic fibers

Fiber type	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	Moisture content (wt%)
Coir	1.15–1.46	95–230	2.8–6	15–51.5	8.0
Kenaf	1.4	223–930	14.5–53	1.5–2.7	9–12
Flax	1.4–1.5	343–2000	27.6–103	1.2–3.3	8–12
Bamboo	0.6–1.1	140–800	11–32	2.5–3.7	8.9
Abaca	1.5	400–980	6.2–20	1–10	5–10
Jute	1.3–1.5	320–800	8–78	1–1.8	12.5–13.7
Sisal	1.33–1.5	363–700	9–38	2–7	10–22
Ramie	1.0–1.55	400–1000	24.5–128	1.2–4	7.5–17
Cotton	1.5–1.6	287–800	5.5–12.6	3–10	7.9–8.5
Banana	1.35	500	12	1.5–9	8.7–12
Hemp	1.4–1.5	270–900	23.5–90	1–3.5	6.2–12
Pineapple	1.5	413–1625	1.5	1–3	11.8
Henequen	1.2	430–570	10.1–16.3	3.7–5.9	—
Kapok	0.38	64	4	1.4–3	9–10.9
Wool	1.32	180–240	2.7–17	0.9–1.1	—
Silk	1.37	340–620	14	18–34	—
Angora	1.4	500–1150	11.8	3.7–4.3	—
Bagasse	1.25	222–290	17–27.1	1.1	8.8
E-glass	2.5	3500	72	2.5–3.4	—
Carbon	1.7	4000	235	1.4–1.8	—
Aramid	1.4	3100	63–67	3.3–3.7	—

Source*:* [85]

2.1.12 Advantages of Natural Fiber Composites [86]

- High Strength

In the construction sector, sturdy metals in all directions, such as steel or aluminum, are used. To manufacture composite materials with superior strength compared to conventional materials, they must be developed using a specific approach.

- Durable

Composites have a long lifespan and require minimal maintenance when used to construct a structure. The average lifespan of composite materials is 50 years. However, neither the duration of a composite construction's durability nor the point at which the original composites are no longer helpful is known.

- Low thermal conductivity

Composites made of natural fibers are effective insulators. Buildings utilize them for doors, windows, and panels to defend themselves from the elements because composites made of natural fibers have poor heat and cold conductivity.

- Weight-related strength

A characteristic of composite materials that identifies them and indicates their densities and weights is their strength-to-weight ratio. Composite materials are lightweight and robust at the same time. As a result, composite materials may also be used in the automotive and aircraft industries.

- Lightweight

Because they are lightweight materials, composites are used in automotive and aeronautical applications. Composite materials are lighter than conventional materials like metals and wood. Modern aircraft designs focus more on fuel efficiency, which can only be achieved using lightweight composite materials.

- Corrosion resistance and high-impact strength

Composites offer strong impact resistance and superior corrosion resistance. It can both absorb anything and withstand weather-related harm. The material is highly resistant to chemicals. In any climate, it could be harmful. Composite materials produce bulletproof jackets, panels, and protective measures for buildings, military vehicles, and aircraft to withstand sudden, high-impact forces effectively. This is primarily due to their exceptional capacity to absorb and mitigate the effects of explosions and other potentially damaging events.

- Dimensional stability

Composites maintain constant conditions of stability. Weather or temperature has little effect on their size or form. On the other hand, when the temperature changes, wood contracts and expands. As a result, composites are used to build aircraft wings because of their excellent ability to adapt to any situation and maintain their shape and size regardless of how hot or cold it is outside.

- Nonconductive

Composites are electrically non-conductive. That implies that composites cannot carry electricity. This property makes circuit boards and electrical utility poles from composite materials. It is often necessary for composite materials to have electrical conductivity, in which case it is simple to change their characteristics to those of a conductive material.

- Nonmagnetic

The fact that composites lack magnetic qualities makes them the sole material that can be utilized to create houses, tables, enclosures for electrical equipment and reinforced concrete for hospital walls and flooring.

- Radar transparent

Radar equipment is made of composites, and composite materials are utilized in radar to transmit signals in the air or on the ground. Composites are crucial in constructing aircraft like the B-2 stealth bomber, which is utilized for signal transmission by the U.S. Air Force.

2.1.13 Opportunities and Challengers

For the following reasons, natural fiber-reinforced composites have recently opened up prospects in automotive sector applications.

- They need a tiny amount of energy to make, unlike glass and other synthetic fibers, and they are environmentally benign and biodegradable.
- The reinforcement density, much lower than that of glass and carbon fibers, is crucial in constructing composites made of plant-based natural fibers.
- Some natural fibers have weight-to-modulus ratios comparable with E-glass fiber, which is advantageous for designs that require a certain rigidity.
- Natural fiber-reinforced composites exhibit superior acoustic damping properties compared to synthetic fibers, rendering them more appropriate for noise reduction, which is a critical requirement in applications within the interior of vehicles.

- Natural fibers are less expensive than synthetic ones.

The advantages of utilizing plant-based natural fibers in composite materials for automotive applications include their low density and cost, versatility, quick availability, decreased abrasion, and ease of waste disposal. Despite efforts to individualize fiber bundles over the last ten years, adhesion has remained a significant difficulty. It has proven challenging to solve in the search for more common usage of natural fibers as reinforcement. Natural fibers' hydrophilic properties harm adherence to a hydrophobic matrix and reduce the overall strength of composites.

There are some difficulties involved in the production and use of natural fiber-reinforced parts.

- For non-woven materials: Variations in fiber quality lead to uneven length distribution, embellishment, and quality and consistency.
- The ineffectiveness of natural fibers as thermal insulators.
- The distinct scent of bio-based polymers and plant-based fibers.
- Resistance to moisture during application and the process.
- Limited ability to battle fires.
- The quality of natural fibers and the parts made from them vary depending on where they are grown and the climate.
- The availability and high quality of natural fiber present challenges.

Additional chemical treatments should be used to overcome difficulties in green composites, such as moisture absorption and poor fiber-matrix interaction.

2.1.14 Uses for natural fiber composites

Natural fiber-reinforced composites are experiencing rapid advancements and emerging as cost-effective alternatives to metal or ceramic materials in various sectors, including automotive, aerospace, marine, sporting goods, and electronics [87]. Natural fiber composites have good particular qualities, although their characteristics are highly variable. With the development of increasingly sophisticated processing methods for natural fiber and their composites, their weaknesses may and will be addressed. In the contemporary era of environmentally friendly materials, the unique

characteristics of natural fiber composites provide a solid groundwork for exploring novel applications and opportunities in biocomposites. The widespread adoption of natural fiber composites in various applications has created new avenues for academia and commercial enterprises to develop sustainable modules that can be integrated with these composites in the future [88]. In the United States, straw is used to make composite construction materials. Straw bales have been utilized in the construction of buildings. At the same time, the automotive industry has already adopted natural composites for various components. These composites typically consist of polyester or polypropylene matrices reinforced with flax, hemp, or sisal fibers. Rather than solely driven by technical requirements, the industry's preference for natural fiber composites is primarily influenced by cost, weight reduction, and marketing considerations [51]. Germany has pioneered natural fiber composites in the automotive industry, with automakers like Mercedes, Audi, BMW, and Volkswagen incorporating them in interior and exterior applications. The early adoption of natural fiber composites in automotive interiors can be seen in the 1999 S-Class Mercedes Benz door panel, constructed using flax, hemp, and sisal fibers. Premium automakers like Mercedes Benz demonstrate their commitment to environmental reasons, showcasing the potential of these sustainable alternatives to traditional materials. Germany's leadership in utilizing natural fiber composites has led to global developments and applications, encouraging other automakers to explore eco-friendly solutions [89]. Mercedes-Benz demonstrated their early adoption of natural fiber composites by introducing an epoxy matrix reinforced with jute in their E-class automobiles back in 1996. This innovative approach reflects their dedication to sustainable materials and their commitment to reducing environmental impact. Jute, a solid and cost-effective natural fiber, is ideal for applications requiring mechanical strength and environmental sustainability. Since then, using natural fiber composites in automotive applications has grown, showcasing Mercedes-Benz's long-term vision for creating environmentally friendly vehicles. With the introduction of Audi's mid-range A2 in 2000, a new paradigm for the commercial application of natural fiber composites was established. It was created with sisal/flax fiber-reinforced polyurethane door trim panels. A sugar cane-based eco-plastic developed by Toyota will be used to line car interiors [90]. The intended application for developing biodegradable bark cloth-

reinforced green epoxy composites is manufacturing vehicle instrument panels [91]. Coir/polyester composites have been used to produce a range of items, including mirror casings, paperweights, projector covers, voltage stabilizer covers, mailboxes, helmets, and roofs. As an environmentally friendly substitute for traditional materials, natural fiber composites are increasingly embraced in structural and infrastructure projects, contributing to their growing popularity. They are used in load-bearing components like beams, roofing, multifunctional panels, water tanks, and pedestrian bridges, offering strength, lightweight construction, sustainability, and corrosion resistance. These composite materials enhance structures' overall sustainability and longevity, simultaneously minimizing environmental impact and enhancing energy efficiency. As demand for eco-friendly construction practices continues to grow, natural fiber composites offer promising solutions for greener and more resilient infrastructure development [92]. The interior of a home or temporary outside work like economical housing for the military, rehabilitation, and transportation can all be done with jute-based green composites, which are even capable of performing fundamental structural employment opportunities. Due to its insulating characteristics, jute finds applicability in various automotive applications, such as car door and ceiling panels and panels that serve as a barrier between the engine and passenger compartments [93].

2.1.15 Chapter Summary

This chapter reviews the literature on natural fiber polymer composites, focusing on their historical research status and current state. It discusses the advantages and applications of natural fibers like jute, hemp, flax, sisal, bamboo, and coir and their compatibility with matrix materials like thermoplastics and thermosetting polymers. The chapter highlights the advantages of natural fiber polymer composites, such as their environmental friendliness, biodegradability, reduced carbon footprint, and potential for recycling. These composites have exceptional mechanical properties, making them appropriate for various industries such as automotive, construction, packaging, and consumer goods. The chapter emphasizes the significance of natural fiber polymer composites as eco-friendly, adaptable, and high-performance replacements for conventional materials.

Natural fiber composites (NFCS) have been shown to have the potential to be an environmentally acceptable substitute for other synthetic composites with minimal environmental impact. Natural fibers are used instead of glass fibers as support in polymer composites. NFCS has much promise in the construction industry and can be used in numerous applications instead of conventional structural materials (such as GRP, steel, and concrete).

Natural fiber-reinforced composites have been used as building materials in the construction industry, one of the biggest consumers of composite materials worldwide. Natural fiber composites are very appealing for innovative structural design because of their many benefits, which range from composite roofing, flooring, ceilings, beams, and columns to complete hybrid construction systems to intelligent insulation building systems.

To create innovative natural fiber composites for future building, significant research has been done on topics ranging from the fundamental interaction between natural fiber and matrix to ultra-lightweight, long-lasting, and fully bio-composites made of natural fibers and biopolymers. Composites with intelligence and multiple uses have attracted a lot of attention.

CHAPTER 3

3.1 Material and Method

3.1.1 Overview of the Experiment

- First Stage

In the first stage of the research, a comprehensive methodology was employed to characterize natural fibers and waste polyethylene for their potential use in composite materials. The physical properties of selected natural fibers were investigated, including kithul, Palmyra, sisal, coir, banana, bamboo, and Watakeiya. Parameters such as fiber density, diameter, water absorption, SEM analysis, and mechanical properties, such as fiber tensile strength, were measured. Subsequently, the chemical properties of the natural fibers were examined by subjecting them to FTIR analysis.

These characteristics play a vital role in assessing the appropriateness of natural fibers for use as reinforcements in composite materials. By analyzing these physical characteristics, researchers gained insights into the fibers' structural integrity, moisture absorption potential, and overall strength.

In addition to natural fibers, waste polyethylene was also characterized, focusing on its chemical properties. Fourier Transform Infrared Spectroscopy (FTIR) was employed to analyze the composition and molecular structure of the waste polyethylene. This analytical technique allowed researchers to identify specific chemical functional groups present in the material and understand its compatibility with the natural fibers. By examining the FTIR spectra, we can gain valuable information about the chemical composition of the waste polyethylene and its potential interactions with the natural fibers during the composite material manufacturing process.

Overall, this initial research stage involved systematically characterizing natural fibers and waste polyethylene, encompassing their physical and chemical properties. These characterizations provided a foundation for subsequent investigations into the

development of composite materials utilizing these materials, ultimately contributing to the advancement of sustainable and eco-friendly manufacturing processes.

- Second Stage

In the subsequent phase of the study, the attention turned to preparing and characterizing polymer composites reinforced with kithul fiber. The methodology involved varying several vital parameters to investigate their impact on the mechanical and physical properties of the composites. These parameters included the fiber ratio, composite processing temperature and pressure, and fiber length.

The effect of incorporating kithul fiber into the polymer matrix at various fiber ratios was evaluated to understand its impact on the resulting composite materials. By varying the amount of fiber, researchers could evaluate the reinforcement potential and determine the optimal fiber content for enhanced mechanical properties. Additionally, composites were processed at different temperatures and pressures to explore their influence on the composite's internal structure, interfacial bonding, and overall performance.

Another variable considered in this stage was the fiber length. By modifying the length of kithul fibers, researchers aimed to understand how it impacted the composite's tensile and flexural properties. Different fiber lengths can affect the fiber dispersion, interfacial adhesion, and stress transfer within the composite, ultimately influencing its mechanical behavior.

In the four-step process, tensile and flexural properties were identified as crucial metrics for evaluating composite materials. These tests provided insights into the composites' strength, stiffness, and deformation characteristics under tension and bending. Researchers could evaluate the performance of the composites as an entire and the efficiency of the kithul fiber reinforcement by assessing these characteristics.

Additional assessments were performed on the chosen composites after identifying the optimal composite formulations based on their mechanical properties. These assessments involved evaluating parameters such as impact resistance, water

absorption capacity, thickness swelling, and flammability characteristics of the composites. These tests provided valuable information regarding the composites' durability, resistance to environmental factors, and fire safety properties.

Researchers used this approach to create kithul fiber-reinforced polymer composites with improved mechanical performance and desirable physical characteristics. The findings from this stage contribute to understanding composite material behavior and aid in developing sustainable and functional materials for various applications.

Stage One - Characterization of Natural Fibers and Waste Polyethylene

3.1.2 Preparation of natural fibers

Sisal, Palmyra, Banana, and Bamboo fibers are readily available to purchase from the manufacturers (Figure 7). Since Watakeiya was not readily available, these fibers were extracted. For this, the Watakeiya leaf was soaked for a week in water. Then, leaves were scraped to extract Watakeiya fibers.

Figure 7: Selected natural fibers

3.1.3 Physical Properties of Fibers

- Fiber Diameter

A software-controlled Metallurgical Microscope was employed to precisely characterize natural fibers' diameter. The diameter measurement process involved selecting thirty randomly chosen fibers for analysis. Using the microscope, three equidistant points were measured on each fiber to ensure the accuracy and reliability of the data.

By measuring multiple points on each fiber, potential variations in diameter along the fiber length could be accounted for. This approach gave a more comprehensive understanding of the fiber's diameter characteristics.

The average diameter was calculated after measuring the diameter of all thirty fibers. This calculation involved summing the individual diameter measurements and dividing by the total number of fibers, yielding the mean diameter value. This mean diameter value represents the average thickness of each fiber, providing a representative measurement of the fiber diameter within the sample set [95].

- Fiber Density

A psychometric approach was employed to characterize the density of natural fibers. The density of the fibers was determined to be an average of 20 fibers. The methodology involved the following steps:

First, the chosen natural fibers were cut into segments with lengths ranging from 5 mm to 15 mm. The fiber segments were subsequently dried for 96 hours in a silica gel desiccator. This drying step ensured that the fibers reached a consistent moisture content before density measurements were taken.

Next, the dried fiber segments were placed in a pycnometer, a specialized container used for measuring the density of materials. The pycnometer was carefully sealed to prevent any air gaps or leaks.

To further eliminate any remaining moisture, the fiber segments were desiccated once more for 24 hours after being placed in the pycnometer. The fiber segments were immersed in a toluene solution for two hours to ensure accurate density measurements. This treatment helped remove any microbubbles that could affect the density readings.

The testing procedure was repeated five times to enhance the density measurements' precision. This repetition allowed for a more robust assessment of fiber density. Finally, the average density value was calculated by summing the individual density measurements and dividing by the total number of measurements [96], [97].

$$\rho_f = \frac{(m_2 + m_1)\rho_t}{(m_3 - m_1)(m_4 - m_2)}$$

M_1 represents the mass of the empty pycnometer in grams,
M_2 represents the mass of the pycnometer filled with cut fibers in grams,
M_3 represents the mass of the pycnometer filled with toluene in grams,
M_4 represents the mass of the pycnometer filled with cut fibers and toluene in grams, and
P_t represents the density of toluene in grams per cubic centimeter, which is 0.866 g/cm³.

- Water Absorption Characteristics of Chosen Natural Fibers

The fibers are thoroughly washed using deionized water to eliminate surface impurities or contaminants. Subsequently, the fibers were dried in an oven at 60°C for 24 hours. This drying procedure aimed to achieve a uniform moisture content and ensure complete moisture removal from the fibers before conducting the water absorption test.

After the completion of the drying process, the fibers were transferred to a desiccator to cool down and reach a state of equilibrium with the surrounding ambient conditions. Cooling the fibers in this manner ensured they were at the same temperature as the surrounding environment before the absorption test commenced.

The fibers were carefully bundled upon cooling, forming a single unit weighing 5 grams. The bundle of fibers was weighed to obtain an accurate starting weight for the water absorption test.

Subsequently, the prepared fiber bundle was submerged in a beaker filled with water at an ambient temperature carefully maintained at 25°C. The fibers were left inside the water for a specific duration to allow water absorption to occur.

Measurements were taken at regular intervals, starting from 2 hours and then at 6-hour intervals. After each measurement, the fibers were returned to the water. This process was repeated until a constant value for water absorption was observed. The constant value indicated that the fibers had reached their maximum water absorption capacity, and further absorption was negligible.

By adhering to this methodology, researchers acquired data concerning the water absorption properties of the natural fibers. This information is crucial for understanding the fibers' ability to absorb and retain moisture. It is significant for assessing their suitability in various applications such as textiles, composites, and other moisture-sensitive environments [98].

$$M_C = \frac{(M_a - M_d)}{M_a}$$

Where;
M_C − Moisture Content,
M_a −Weight of the fiber after dipping in water, and
M_d − Dry fiber sample weight.

- SEM (Surface Morphology and Cross Sections)

Scanning electron microscopy (SEM) was a powerful tool to investigate the fibers' cross-sectional characteristics and surface morphology. In this analysis, SEM allows for high-resolution imaging, enabling researchers to observe the intricate details of the fibers at various magnifications.

SEM imaging was utilized to investigate the surface morphology of the fibers. This involved capturing longitudinal views of the fibers, allowing researchers to observe the surface texture, fiber diameter, and surface features such as roughness, cracks, or irregularities. The SEM images reveal detailed information about the fibers' external structure and surface properties, which can influence their functionality and interaction with other materials in composite systems [99].

3.1.4 Mechanical Properties of Fibers

- Tensile strength

The ASTM D 3822 - 07 standard was followed during the tensile test. The tests were conducted using an INSTRON tester, a Universal Tensile Testing Machine. The tests were conducted in a controlled environment with a 25°C temperature and a 65% relative humidity level. The samples were set with a gauge length of 50 mm to ensure consistent measurement in the designated region.

The testing machine's crosshead speed was adjusted to 5.0 mm/min, establishing the rate at which the samples underwent tension during the experiment. A static load of 50N was applied to the kithul fibers during the test. This load provided a reliable and repeatable basis for measuring tensile properties.

To ensure statistical significance and accuracy, 35 samples were tested for each fiber type. This larger sample size helped to obtain a more appropriate and representative value for the measured tensile properties [97].

Throughout the tensile tests, several parameters were measured, including tensile strength and Young's modulus. Tensile strength represents the maximum stress a material can endure before fracturing, whereas Young's modulus indicates the material's stiffness.

3.1.5 Chemical Properties of Fibers

- FTIR (Fourier Transform Infrared Analysis)

The FTIR spectrometer was used to analyze the matrix's Fourier transform infrared (FTIR) spectra, with a scan rate of 32 scans per minute. The spectrometer's resolution was set to 4 cm^{-1}, indicating its ability to distinguish fine details in the spectral data. The investigation included wavenumbers between 4000 and 500 cm^{-1}, often pertinent for detecting functional groups in organic compounds. The size and shape of peaks observed in FTIR analysis play a significant role in identifying functional groups in fibers or other analyzed materials. Different functional groups exhibit characteristic absorption peaks at specific wavenumbers, providing valuable information about chemical bonds and molecular structures. By utilizing an FTIR spectrometer with the specified parameters and analyzing the resulting spectra, researchers can gain insights into the functional groups present in the fibers of interest, aiding in the characterization and understanding of the fiber's chemical composition, as well as further investigations related to its properties and potential applications.

3.1.6 Chemical Properties of Waste Polyethylene

- FTIR (Fourier Transform Infrared Analysis)

The Fourier transform infrared (FTIR) spectroscopy was employed to analyze the specified matrix's infrared (I.R.) spectrum. The analysis was conducted using an FTIR spectrometer operating at a scanning rate of 32 scans per minute and a resolution of 4 cm^{-1}. The wavenumber range examined spanned from 4000 to 500 cm^{-1}.

By subjecting the polythene sample to FTIR analysis, researchers aimed to identify the specific functional groups present in the material. Identifying these functional groups is facilitated by observing the size and shape of the peaks obtained in the I.R. spectrum.

Different functional groups exhibit characteristic absorption peaks at specific wavenumbers, allowing spectral analysis to identify them. By comparing the observed peaks in the I.R. spectrum of polythene to established reference data and known

functional groups, researchers could determine the types of chemical bonds and functional groups in the polythene sample.

The size and shape of the peaks in the FTIR spectrum provided valuable information about the molecular structure of the polythene material, aiding in the characterization and understanding of its chemical composition. This analytical technique is widely used in various fields, including materials science, polymer chemistry, and quality control, to elucidate organic compounds' molecular characteristics and functional groups.

Stage Two – Preparation of Kithul Fiber Reinforced Polymer Composite

3.1.7 Selection of natural fibers

Out of these natural fibers, Kithul fiber was selected for the production of composites. We could only find one study of kithul fiber application in 2019: a conventional concrete block. In Sri Lanka, the kithul truck core and the jaggery palm are used to make jaggery and treacle. However, the kithul husk was eliminated after using other parts of the kithul tree. Therefore, husks can be used to extract kithul fibers.

Because of these two reasons, kithul fiber was chosen as a natural fiber for this investigation.

3.1.8 Preparation of kithul fiber

Kithul fibers were extracted from the husk of the kithul tree and husks were collected from Aththanagalla Temple in Sri Lanka for this research study. Figure 8 illustrates kithul husk and kithul fiber.

The fiber was cleaned well to remove residual particles and adhered dust from the fiber surface. To accomplish this, the fibers were subjected to washing in flowing, drinkable water for approximately 30 minutes, followed by air-drying at ambient room temperature. These thoroughly cleaned kithul fibers were used to check the properties

of kithul fiber and develop a composite material. Cleaned kithul fibers were cut into small pieces (2.5 cm – 3.5 cm) to get uniformity in the mixed sample of composite.

Figure 8: Collected Kithul fibers

- Preparation of polyethylene

Waste polyethylene was gathered from particular factories (Figure 9) and cleaned in clean water with washing powder to remove impurities and unwanted material. Before using the cleaned polyethylene, it was allowed to dry naturally in the air. Cleaned polyethylene was shredded to get uniformity of the mixed sample of composite.

Figure 9: Purchased Polyethylene

3.1.9 Manufacturing of laminate sheets

The hand layup method was used to lay the kithul fiber on waste polyethylene sheets, and a hot press machine was used to make the laminated sheets using the compression molding technique. The waste polyethylene and kithul fiber were compressed at 140°C for about 2 minutes during this process.

Twenty samples were prepared in seven mixed proportions to identify the suitable kithul polyethylene waste proportion to manufacture composites. Feeding the material to the hot press was performed manually and handled according to the given safety precautions. The hot press equipment and laminated sheets are shown in Figure 10.

Figure 10: Hot Press Machine and Prepared Laminated Sheets

Then, the prepared samples were shredded using a shredder machine [Figure 10]. The process of shredding aids in keeping the material uniform. Then, the shredded materials were uniformly stacked in a steel mold using the hand layup method. The final composite samples were prepared using a hot-pressed machine.

3.1.10 Manufacturing of composite materials

Step 1: Select a suitable kithul weight fraction (% of the total weight)

During the procedure, a pressure of 25 pounds per square inch (psi) load was applied in a hot press machine, as shown in Figure 11. The hot press machine is designed to apply pressure and heat to the composite materials to facilitate their consolidation and bonding.

The pressure of 25 psi was selected based on the requirements of the experiment and the desired level of compaction and consolidation of the composite layers. The application of pressure promotes proper contact and adhesion between the kithul fiber and waste polyethylene, forming a cohesive and structurally strong composite.

Besides the applied pressure, the hot press machine was adjusted to a temperature of 150°C. The elevated temperature aids in softening the polyethylene and facilitating the flow and diffusion of polymer chains, promoting intermolecular bonding and consolidation of the composite structure.

The duration of the pressing process was set to 6 minutes. This time interval allows for sufficient heat transfer and bonding between the kithul fiber and the waste polyethylene layers. It ensures the composite material undergoes the necessary transformation and achieves the desired mechanical and physical properties.

Figure 11: Hot Press machine and prepared composite board

The mixing proportions of kithul and waste polyethylene are shown in Table 5.

Table 5: Sample preparation plan according to the kithul weight fraction (% of total weight)

Sample Number	Kithul Fiber (g)	Waste Polyethylene (g)	Kithul Weight Fraction (% of total weight)	Number of samples
1	0	10	0%	20
2	0.25	9.75	2.5%	20
3	0.5	9.5	5%	20
4	1.0	0.9	10%	20
5	2.0	0.8	20%	20

6	3.0	0.7	30%	20
7	4.0	0.6	40%	20

After being prepared, the composite boards were kept in the cooler to cool until they reached room temperature. The prepared laminated sheets and the final composite samples are shown in Figure 11.

Step 2: Select a suitable composite processing temperature (°C)

The chosen kithul: Polyethylene ratio from the previous stage was used to make composites in this phase, but the processing temperature was changed according to Table 6. Following the guidelines of ASTM D 3039, six specimens were manufactured for the tensile strength test, with dimensions of 250 mm in length, 25 mm in width, and 2.5 mm in thickness. These samples were carefully fabricated to meet the specifications outlined in the standard for conducting tensile testing on polymer composites.

Similarly, six specimens were prepared for the bending test, featuring measurements of 150 mm in length, 12.7 mm in width, and 3.2 mm in thickness. These samples were intentionally crafted to adhere to the specifications outlined in ASTM D 3039 for performing bending tests on polymer composites.

Table 6: Sample preparation plan according to the composite processing temperature (°C)

Sample Number	Kithul Fiber (g)	Waste Polyethylene (g)	Kithul Weight Fraction (% b total weight)	Composite Processing Temperature (°C)
1	1.0	0.9	10%	145°C
2				150°C
3				155°C
4				160°C
5				165°C
6				170°C

Step 3: Select suitable composite processing pressure (tons)

In this step, composites were created using the specified kithul: polyethylene ratio from the previous stage, but the processing pressure was changed according to Table 7.

Under the specifications of ASTM D 3039, five samples were prepared for the tensile test. Each sample had measurements of 250 mm in length, 25 mm in width, and 2.5 mm in thickness. These dimensions were meticulously followed to meet the requirements specified in the standard for conducting tensile testing on polymer composites.

Additionally, a separate set of five samples was prepared for the bending test. These samples had different measurements than those used in the tensile test. Each sample employed in the bending test had dimensions of 150 mm in length, 12.7 mm in width, and 3.2 mm in thickness. These measurements were selected following the guidelines outlined by ASTM D 3039 for conducting bending tests on polymer composites.

Table 7: Sample preparation plan according to the composite processing pressure (tons)

Sample Number	Kithul Fiber (g)	Waste Polyethylene (g)	Kithul Weight Fraction (% b total weight)	Composite processing pressure (tons)
1	1.0	0.9	10%	20
2				25
3				30
4				35
5				40

Step 4: Select a suitable kithul fiber length

Kithul fiber length varied from 0.5mm to 30mm after the processing temperature, pressure, and ratio were determined. According to the tensile and flexural strength standards, six samples with varied fiber lengths were created (Table 8).

Table 8: Sample preparation plan according to the fiber length (cm)

Sample Number	Fiber Length (cm)	Kithul Fiber (g)	Waste Polyethylene (g)	Kithul Weight Fraction (% b total weight)	Composite processing pressure (tons)	Composite Processing Temperature (°C)
1	5mm	1.0	0.9	10%	25tons	150°C
2	10mm					
3	15mm					
4	20mm					
5	25mm					
6	30mm					

3.1.11 Tensile Strength

The tensile test specimens were prepared to assess the polymer composite material's stretching or elongation behavior until it reached its breaking point. The test used a 1000N load cell and a 20 mm/min stroke rate. The specimens had dimensions of 250 mm, 25 mm, and 2.5 mm (Figure 12), following ASTM D 3039 guidelines. An extensometer with a 50 mm gauge length was attached to measure strain during the test. The specimen was exposed to a consistent tension load, with a displacement rate of 20 mm/min.

The extensometer measured the elongation or stretching of the specimen within the specified gauge length, allowing the calculation of strain. By following ASTM D 3039 and using an appropriate load cell, stroke rate, specimen dimensions, and extensometer

with a defined gauge length, the tensile test provided valuable information about the polymer composite material's mechanical properties, including its elongation characteristics until failure.

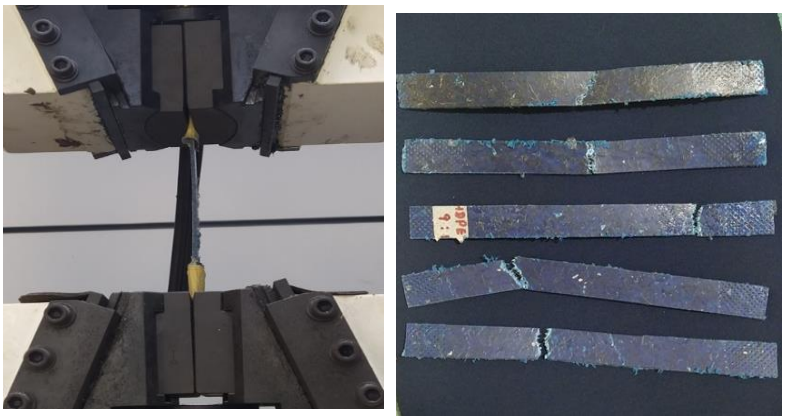


Figure 12: Tensile strength machine and tensile test specimens

3.1.12 Three-Point Bending Strength

A universal testing T-machine was used to evaluate flexural strength under ASTM D790 utilizing a three-point bending method. The samples have dimensions of 127mm x 12.7mm x 3.2mm. As depicted in Figure 13, the distances between the supports were 100 mm, and the strain rate was 5 mm/min [99].

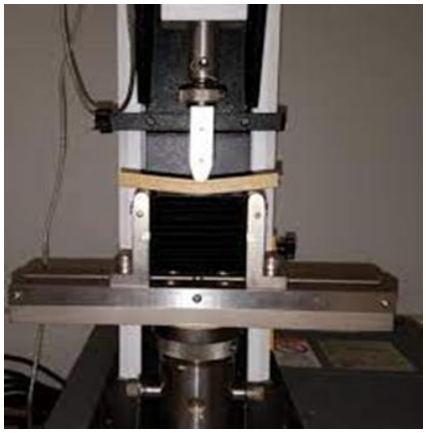


Figure 13: Universal testing T-machine

3.1.13 Impact Test

To evaluate material resistance, notch-A Izod impact strength tests are carried out following ASTM D256. Three specimens with dimensions of 64mm x 12.7mm x 3.2

mm are used in this test. The Izod impact strength was identified by averaging the findings of each sample.

The Izod impact test involves striking the specimen with a pendulum that is firmly held vertically and has a weighted end swinging down on it [101]. Figure 14 shows the impact test device and V-notch marker. The energy of the pendulum is precisely calculated to determine the impact strength by calculating the height loss during the swing [102].

Impact strength is a crucial parameter in evaluating polymer composites' ability to resist fracture or breaking under high-energy impact. It is impacted by the characteristics of individual fibers as well as the adhesion between layers and interfaces within the composite structure. Researchers must select suitable fibers for hybridization, as they possess varying mechanical properties. Interlinear and interfacial adhesion are crucial for stress transfer and load distribution during impact events. Enhancing interlinear and interfacial adhesion is essential for improving impact performance. By understanding and controlling these factors, researchers can design composite materials with superior impact resistance, making them suitable for high-energy impact applications like aerospace, automotive, sports equipment, and protective gear.

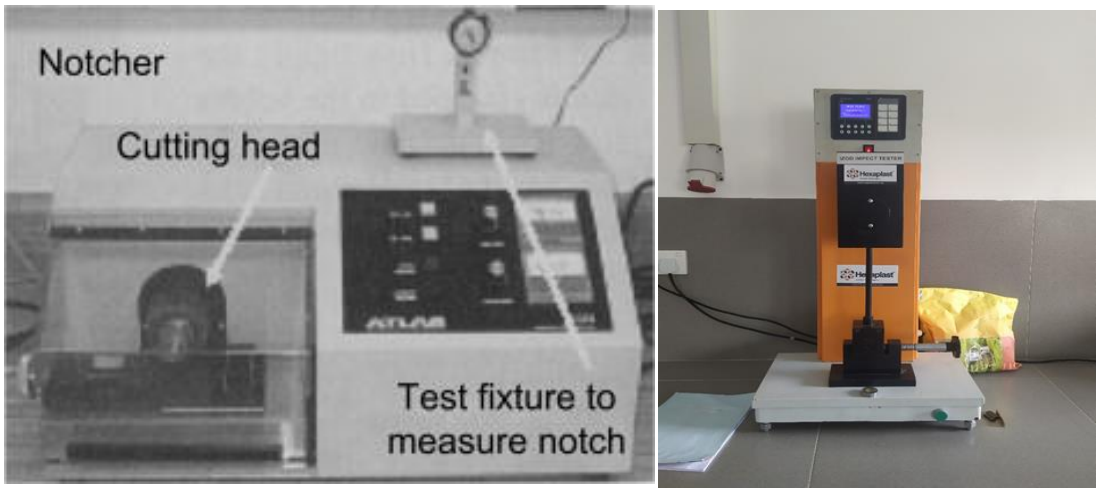


Figure 14: V-notch marker and Cantilever Beam (Izod –Type) Impact Machine

3.1.14 Water Absorption

To assess the water absorption properties of composites reinforced with kithul fibers, water absorption tests were carried out following the ASTM D 570 standard. The saturation point was reached after the composite samples were submerged in a water bath for a predetermined amount of time. Six examples with dimensions of 76.2mm x 25.4mm x 3.2mm were cut from composite panels. Two sample series were performed to identify the locations in the composite sample with the highest water absorption rates (Edges or Surface). The first one is all 4 edges and two surfaces of samples exposed to water and the second one is two surfaces exposed to water and the other 4 sides are properly sealed with waterproofing material (Flex 100 Waterproofing).

Following a 24-hour drying period in an oven set at 50°C, the samples were cooled to room temperature. The drying process was repeated until the specimen weight reached a stable and constant state, referred to as mass Wo. After being in the water for 24 hours, the samples were taken out and immediately dried with a dry cloth before being weighed (mass Wt) on a digital scale. Repeating this process until water absorption reached a constant amount, the specimens were weighed regularly (mass t).

The amount of weight gain over time was computed and plotted against the square root of the time spent submerged. Therefore, it was reported as the average value. The following measurements were made to determine the weight difference between the sample under dry circumstances and the sample after being submerged in water at time t:

$$Mt(\%) = \frac{Wt - Wo}{W0}\ x\ 100\%$$

Where:

Wt represents the weight of the sample at a specific time during water immersion.

Wo represents the weight of the dry sample at the initial time before immersion.

To calculate the water absorption percentage, the weight gain (Wt - Wo) is divided by the initial weight (Wo) and multiplied by 100 to express the result as a percentage.

Figure 15: Analytical balance with the test specimen

3.1.15 Thickness Swelling Test

The thickness swelling of Kithul fiber-reinforced polymer composites can be evaluated using the formula for thickness swelling after a specific period of immersion. This formula, expressed as (T1 - T0) / T1 * 100%, provides a percentage value that indicates the change in thickness of the composite material after 6 days of exposure to a liquid or moisture.

In this formula, T1 represents the thickness of the composite after the 6-day immersion period, while T0 represents the initial thickness of the composite before immersion. By subtracting the initial thickness from the thickness after immersion and dividing it by the thickness after immersion, the relative change in thickness is obtained. Multiplying this value by 100 converts it into a percentage, allowing for easier comparison and interpretation.

The calculation of the thickness swelling percentage provides valuable information about the dimensional stability and water absorption behavior of polymer composites reinforced with Kithul fibers. Higher percentage values indicate a greater extent of swelling, suggesting a higher susceptibility of the material to moisture absorption and potential dimensional changes.

By conducting thickness swelling tests and employing this formula, can assess the performance and suitability of Kithul fiber-reinforced polymer composites in applications where exposure to moisture or liquid environments is a concern. This information aids in designing and selecting materials that can maintain their structural integrity and dimensional stability over extended periods of use.

3.1.16 Flammability Test

Testing for horizontal UL-94 flammability on polymer composite materials is done following ASTM D635. A flammability test necessitates a specimen measurement of 125x13x33 mm. The material is fixed in a horizontal position for the test with the aid of a stand. The specimen is ignited with a Bunsen flame. The specimen is ignited at the open end and left to burn for ten seconds before the fire is put out and allowed to spread throughout its length [97]. A stopwatch can be used to determine how long it will take the object to burn from 25 mm to 100 mm. For each of the three specimens, this procedure is repeated, and the accompanying equation is used to determine the material's burning rate.

$$Rate\ of\ burning\ \left(\frac{mm}{\mathrm{Min}}\right) = 60\ x\ \frac{Length\ of\ the\ sample\ burnt(mm)}{Sample\ burning\ tim\ (s)}$$

CHAPTER 4

4.1 Results and Discussion

There are two sections divided by the results.

- Section 01: Characteristics of the selected natural fibers and waste polyethylene.

4.1.1 Characteristics of the selected natural fibers

A comprehensive testing program was conducted to understand the properties of kithul fiber and determine whether it exhibits similarities or differences with other natural fibers. The testing focused on physical, mechanical, and chemical properties to assess various aspects of the selected fibers (Sisal, Coir, Watakeiya, Banana, Bamboo, Palmyra, and Kithul). To gain insights into the physical characteristics of kithul fiber in comparison to other chosen natural fibers, various physical properties such as fiber diameter, density, and moisture absorption were measured and analyzed. These properties help us understand the fiber's structural integrity, handling, and moisture sensitivity. The mechanical properties of the tensile strength of selected fibers were evaluated to determine the fiber's strength and flexibility. Comparing these mechanical properties with other natural fibers allows for a comparative analysis of their performance under load and deformation. Chemical properties, such as the FTIR test, are assessed to understand the fiber's chemical stability and compatibility with different environments and applications. This analysis helps determine the fiber's suitability for specific industries and potential interactions with the composite matrix.

By systematically testing kithul fiber alongside other selected natural fibers, a comprehensive understanding of its physical, mechanical, and chemical properties was obtained. This allowed for a comparative assessment of the similarities and differences between kithul fiber and other fibers.

4.1.2 Characteristics of the waste polyethylene

FTIR testing is essential for selecting the right polyethylene type from waste materials for natural fiber-reinforced polymer composites. It helps identify the specific type, such as HDPE, LDPE, or LLDPE and helps to choose the most suitable matrix for compatibility and optimal performance. FTIR analysis also helps assess material quality and purity, enabling the development of composites with desired properties and enhanced performance.

- Section 2: This section provides a discussion on the characteristics of the developed polymer composites reinforced with kithul fiber.

Among the selected natural fibers, kithul fiber was chosen to develop fiber-reinforced polymer composites for several reasons. Firstly, kithul fiber was selected due to its availability. It is readily obtainable as a byproduct of kithul production, making it a sustainable and easily accessible resource. In addition to availability, kithul fiber possesses excellent properties that make it suitable for composite development. One notable property is its low water absorption. Kithul fiber has inherent hydrophobic characteristics, which means it has a reduced tendency to absorb water compared to other natural fibers. This property contributes to the composite's dimensional stability and resistance to moisture-related issues such as swelling or degradation.

Another advantageous property of kithul fiber is its low density. Kithul fibers have a relatively low mass, which can help reduce the overall weight of the composite materials. This is particularly beneficial in applications where weight reduction is desirable, such as automotive or aerospace industries. Additionally, using waste kithul fibers is essential in selecting kithul fiber for composite development. As waste material from kithul production, these fibers are not commonly utilized and often go to waste. By incorporating them into fiber-reinforced polymer composites, the waste kithul fibers can be repurposed and contribute to the circular economy, promoting sustainability and reducing environmental impact.

Kithul fiber-reinforced polymer composites underwent various tests to evaluate their properties and performance. These tests included tensile, flexural, impact, thickness

swelling, water absorption, and flammability tests. Tensile tests measured the composite's resistance to stretching forces, while flexural tests assessed its bending and flexing properties. Impact tests assessed the composite's toughness and resistance to sudden impacts, while thickness swelling tests measured its dimensional stability in humid or wet environments. Water absorption tests assessed the composite's susceptibility to water uptake, while flammability tests assessed its fire resistance. These tests provided comprehensive data on the composites' mechanical, physical, and fire-related properties, aiding in understanding their behavior, strengths, and weaknesses and guiding further optimization and application-specific modifications.

SECTION 01

PHYSICAL, MECHANICAL, AND CHEMICAL PROPERTIES OF NATURAL FIBERS

4.1.3 Physical Properties of Natural Fibers

To analyze fibers' mechanical and chemical properties, measuring their physical characteristics, including diameter, density, water absorption, and scanning electron microscopic (SEM) analysis is essential. Diameter measures the thickness or width of fiber strands, which affects properties like tensile strength, flexibility, and surface area. Density is crucial for understanding buoyancy, porosity, and thermal insulation. Water absorption measures the fiber's interaction with moisture, providing insights into moisture resistance, swelling behavior, and potential applications in wet or humid environments. SEM analysis examines the fiber's surface and internal structure at high magnification, revealing morphology, surface topography, and inter-fiber interactions. These measurements provide a foundation for further investigations into fibers' properties, aiding their selection, optimization, and application in various industries.

- Diameter of the natural fibers

Since it directly impacts mechanical properties, including tensile strength, flexibility, and stiffness, measuring the diameter of natural fibers is essential for developing natural fiber-reinforced composites. Smaller fiber diameters possess higher surface

area-to-volume ratios, whereas larger diameters offer improved load-bearing capabilities. Understanding the diameter helps select appropriate fiber types and sizes that align with the desired mechanical properties of the composite material. It also influences dispersion and distribution within the polymer matrix, ensuring better dispersion and reduced susceptibility to defects. Understanding the diameter also influences processing and manufacturing techniques, allowing for adjustments in mixing parameters and alignment to achieve desired composite properties.

The values obtained for each fiber within three consecutive distances are shown in Table 9. Figure 16 displays the diameter of banana fiber as measured using an optical microscope. The calculated average diameter of the fibers was obtained 430.6836µm, 523.0138µm, 503.8371µm, 201.9625µm, 403.0454µm and 156.996µm for Kithul, Palmyra, Sisal, Bamboo, Watakeiya and Banana respectively. The highest diameter value can be seen in the fiber Palmyra.

Table 9: Diameter values of the selected fibers

Name	Point 1(µm)	Point 2 (µm)	Point 3(µm)	Average(µm)
Kithul	450.6738	409.7325	431.6446	430.6836
Palmyra	553.6825	344.5431	670.8158	523.0138
Sisal	111.9981	929.7433	469.77	503.8371
Bamboo	245.3267	165.1717	195.3892	201.9625
Watakeiya	343.4462	468.6167	397.0733	403.0454
Banana	139.7875	156.6893	174.5113	156.996

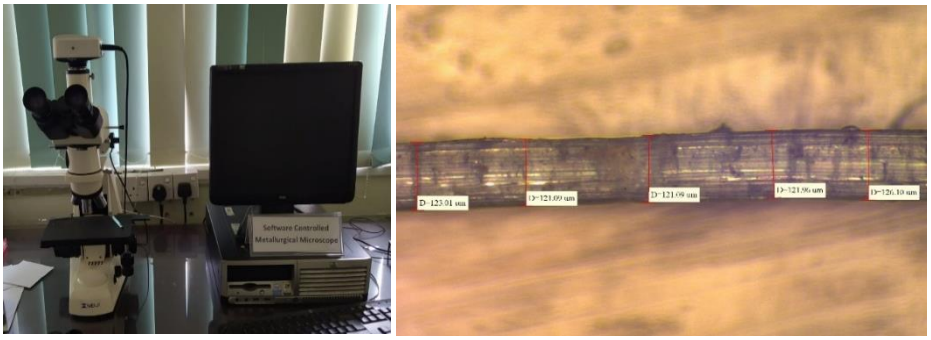


Figure 16: Software-controlled Metallurgical Microscope and diameter measurement of Banana fiber

Due to several factors, Kithul, Palmyra, and sisal fibers have higher diameter values than natural fibers. These include their origin from specific plant sources, which naturally produce larger fibers with larger diameters due to unique structural and physiological characteristics. The cell wall composition in these fibers differs from other natural fibers, containing higher amounts of cellulose, lignin, and other structural components, resulting in increased fiber diameter. The maturity stage at which these fibers are harvested also influences their diameter. Kithul, Palmyra, and sisal fibers are often obtained from mature plant sources, where they have undergone significant growth and development, accumulating more substantial and thicker fibers. The extraction techniques used to extract fibers from the plant source can also impact their diameter, with some techniques like decorticating or retting resulting in larger diameters due to the separation process and removal of non-fibrous materials.

Drawing from the insights presented in Satyanarayana & Wypych, Table 10 presents a compilation of the diameters of various natural fibers, with specific emphasis on kithul fiber [103]. According to Table 10, kithul fiber has a diameter range comparable to that of coir, and others is roughly 10–20 times that of cotton, flax, hemp, Palmyrah, and glass fiber.

Table 10: Diameter of natural fibers

Type of fibre	Fibre diameter (μm)
Coir	100–450
Cotton	19
Flax	19
Hemp	25
Jute	18–20
Palmyrah	8
Sisal	100–300
Glass fibre	15

Source: [103]

- Density of natural fibers

The density of natural fibers plays a substantial role in shaping the development of composites reinforced with these fibers. It directly affects the overall density and weight of the composite material, making it crucial for automotive and building applications. Selecting lower-density natural fibers can create lightweight composites with improved fuel efficiency, payload capacity, and performance. Higher-density fibers contribute to stiffness, strength, and fiber volume fraction, while lower-density fibers may cause uneven distribution and lower mechanical performance. Understanding the density of natural fibers is essential for selecting suitable natural fibers and developing composites with desired characteristics, such as weight reduction, improved mechanical performance, and enhanced processing capabilities.

The average density value of the selected natural fibers was gained 0.904g/cm3,1.1g/cm3,0.88 g/cm3, 1.159 g/cm3, 0.966 g/cm3, 0.762 g/cm3, and 1.15 g/cm3 for Kithul, Coir, Palmyra, Sisal, Bamboo, Watakeiya and Banana respectively (Table 11).

Table 11: Density values of the fibers

Name	**Density (g/cm^3)**
Kithul	0.904
Coir	**1.100**
Palmyra	0.880
Sisal	1.159
Bamboo	0.966
Watakeiya	0.762
Banana	1.150

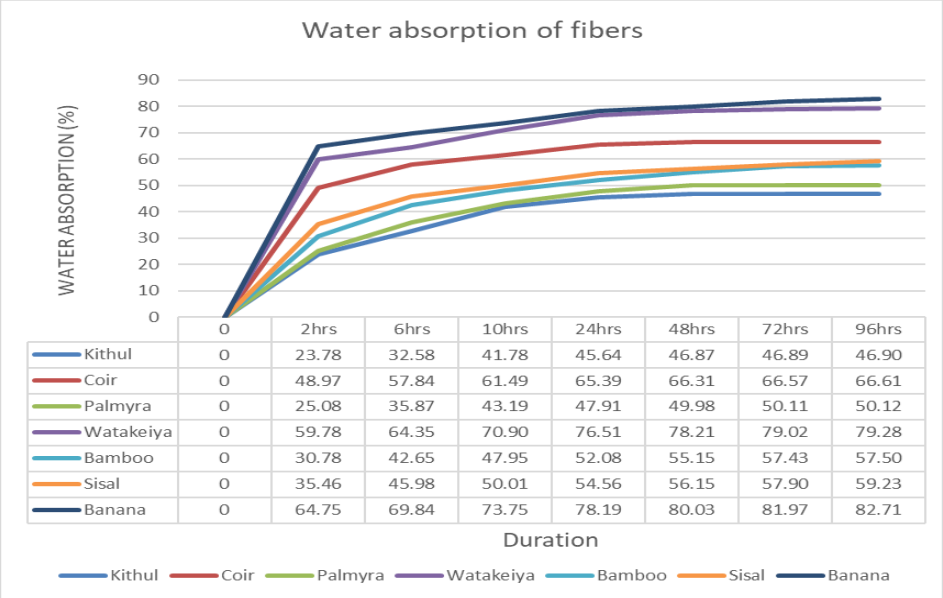
These natural fibers could be utilized to strengthen composites as they are being created. The advantages of being lightweight, reviewable, and biodegradable would then be added [96]. When conducting research, it is crucial to compare density measurements with those of other natural fibers for accurate assessment and analysis.

Commonly used synthetic fibers have densities of 2.56 g/cm³ for carbon fiber and 1.4–1.8 g/cm³ for e-glass fiber, respectively [104]. Therefore, observed natural fiber densities are higher than e-glass fibers but lower than carbon fiber densities.

The growth rate and the environmental condition would reason for differences in density values [105]. Additionally, the variations in densities can be explained by elements including the moisture content of the fibers, the technique used to extract the fibers, and the soil conditions in which the plants were produced [99].

- Water Absorption

Figure 17 displays the water absorption test results of the selected 7 fibers after soaking the samples in water after 2 hours, 6 hours, 10 hours, 24 hours, 48 hours, 72 hours, and 96 hours.



	0	2hrs	6hrs	10hrs	24hrs	48hrs	72hrs	96hrs
Kithul	0	23.78	32.58	41.78	45.64	46.87	46.89	46.90
Coir	0	48.97	57.84	61.49	65.39	66.31	66.57	66.61
Palmyra	0	25.08	35.87	43.19	47.91	49.98	50.11	50.12
Watakeiya	0	59.78	64.35	70.90	76.51	78.21	79.02	79.28
Bamboo	0	30.78	42.65	47.95	52.08	55.15	57.43	57.50
Sisal	0	35.46	45.98	50.01	54.56	56.15	57.90	59.23
Banana	0	64.75	69.84	73.75	78.19	80.03	81.97	82.71

Figure 17: Results of water absorption of natural fibers

Watakeiya, Sisal, and Bamboo fibers exhibit the highest water absorption rate among the tested natural fibers. This implies that these fibers exhibit a higher inclination to absorb moisture when subjected to humid or wet environments. On the other hand, Kithul, Coir, Palmyra, and Banana fibers have demonstrated a lower absorption rate, indicating that they are relatively more resistant to water absorption.

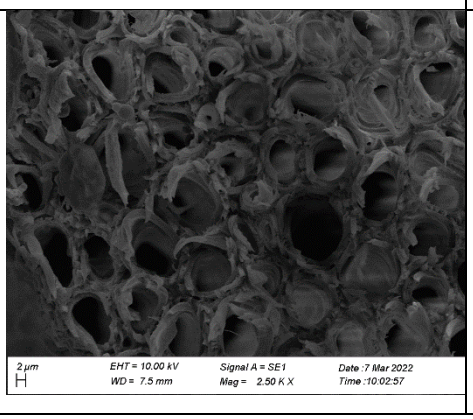
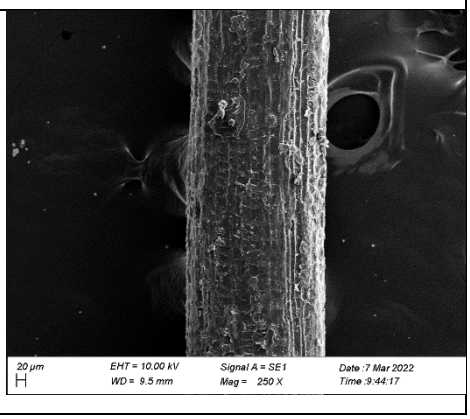
When creating composites reinforced with natural fibers, it is crucial to consider the water absorption properties of the natural fibers. Elevated water absorption can result in dimensional alterations, swelling, and a decline in the mechanical properties of the composite material. Furthermore, it can lead to degradation, mold formation, and diminished durability in applications where exposure to moisture is probable.

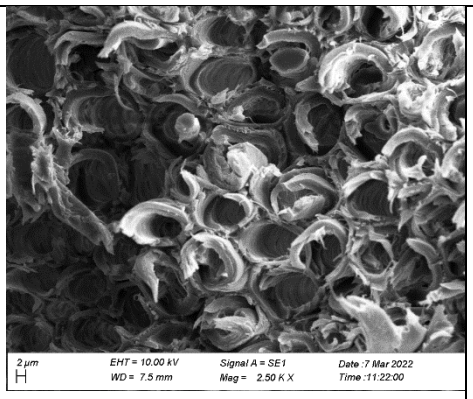
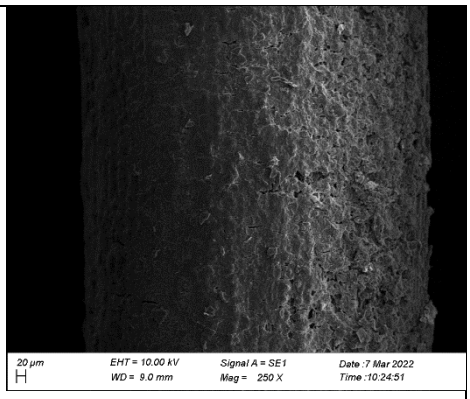
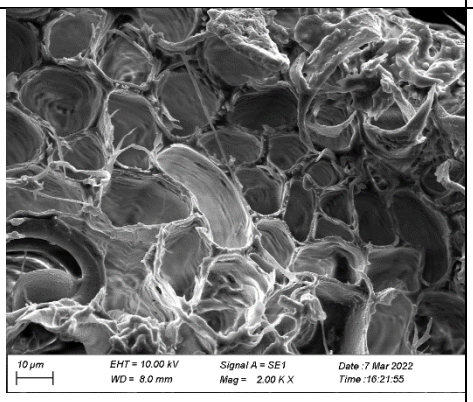
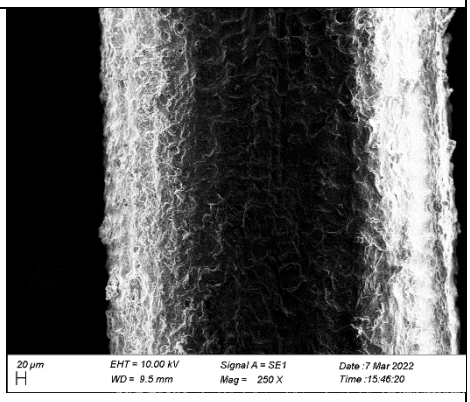
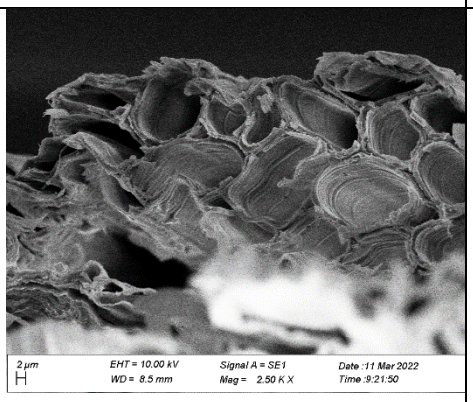
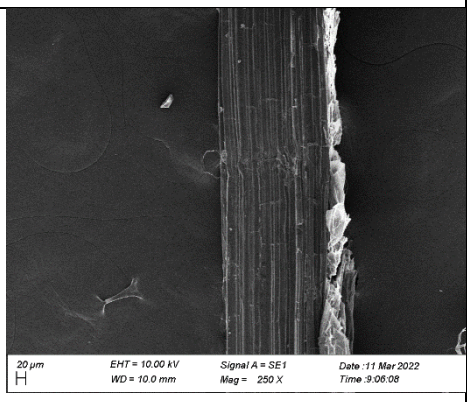
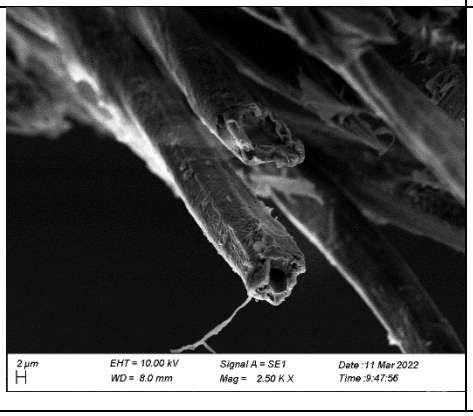
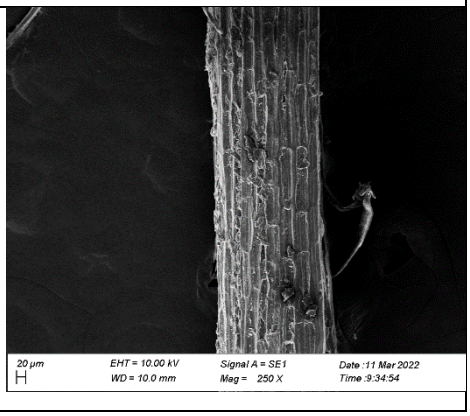
By identifying the water absorption rates of different natural fibers, researchers can select suitable fibers for specific applications. For instance, fibers with low water absorption properties, such as Kithul, Coir, Palmyra, and Banana, may be preferred in applications where moisture resistance and dimensional stability are critical, such as outdoor structures or water-resistant components.

- Scanning Electron Microscopic analysis (SEM)

In the process of creating composites, natural fibers are used as reinforcement material. Because of the age of the fibers, ecological influences, and soil fluctuation, the surface irregularities of the fibers may be caused during the extraction process. As a result, the maker must closely follow the sample preparation process [106]. An electron beam is used by the scanning electron microscope (SEM) to provide incredibly detailed images of the cross-section and longitudinal surface of the fibers [107].

Table 12: SEM images of the cross-section and longitudinal surface of the chosen fibers

Fiber Type	Cross Section	The Longitudinal Surface
Coir		

Kithul		
Palmyra		
Banana		
Sisal		

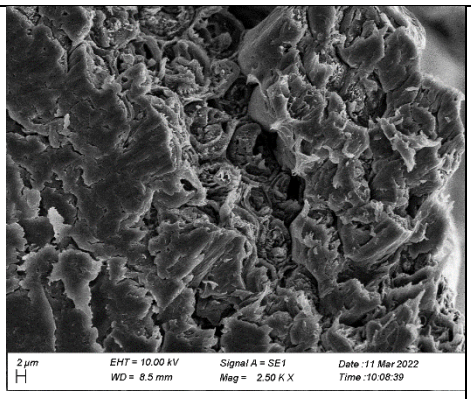
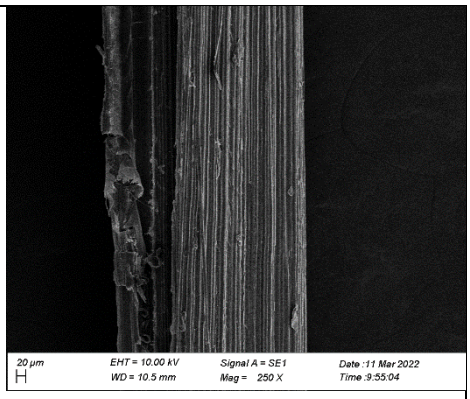
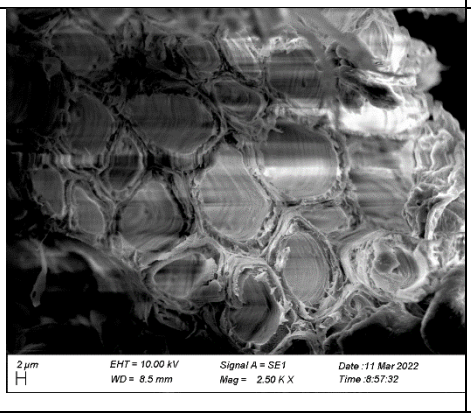
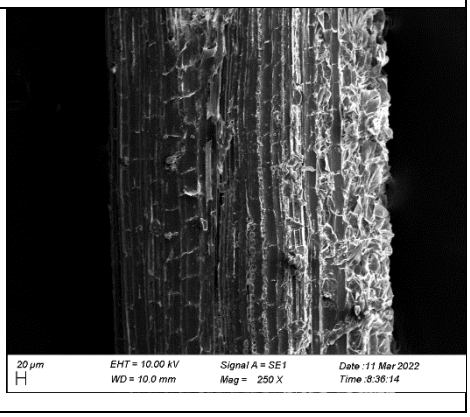
Bamboo		
Watakeiya		

Table 12 provides images from the SEM of the longitudinal surface and cross-sectional area of the selected fiber samples. When observing the cross-sectional images from the SEM analysis, many channels and holes can be identified. Surface irregularities can cause various extraction processes, soil variations, phases of the fiber, and biological effects of the fibers [106].

For determining the longitudinal micrographs of selected natural fibers. Coir, Kithul, Palmyrah, and Watakeiya fibers have a rough surface structure. Banana, Sisal, and Bamboo fibers have relatively smooth surfaces. Smooth fiber surfaces prevent the fiber and matrix from adhering properly. So, throughout the composite fabrication process, surface modification is required to produce the fiber's desired mechanical properties [105] [108]. Conducting composite research needs a detailed analysis of critical aspects such as mechanical properties, pore size, interfacial bonding between the fiber and matrix, surface roughness, and chemical composition [109].

4.1.4 Mechanical Properties of Natural Fibers

- Tensile Strength

The tensile strength of fibers is an important mechanical parameter to observe in natural fibers. Variations in the tensile values of natural fibers can be attributed to several factors, including test conditions, fiber diameters, and the species from which the fiber was taken [106, 97]. The gauge lengths of the 30 fiber samples that were examined ranged from 1 cm to 5 cm. It is important to acknowledge that as the length increases, the cross-section undergoes a corresponding change. Then, it is impacted by changes in tensile strength [106].

Table 13 displays the findings of the obtained tensile test and Young's modulus. The higher tensile strength can be found in Banana and Sisal fibers having values of 772.5 mpa and 586 mpa respectively. These two fibers contain the highest Young's Modulus of 29.46 gpa and 10.18 mpa. Past literature has obtained the tensile strength and the Young's Modulus values of the coir fiber vary from 91-159 mpa and 1.2-1.8 mpa respectively.

Table 13: Tensile strength and Young's Modulus of the fibers

Sample No	**Name of the Fiber**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**
1	Kithul	25.6845	2.416
2	Palmyra	53.935	6.146
3	Watakeiya	156.9	8.78
4	Banana	772.8	29.46
5	Bamboo	273.3	14.9
6	Sisal	586	10.18
7	Coir	88.194–159	1.2–1.8

Banana and Sisal fibers have the highest tensile strength, while Kithul and Palmyra have lower tensile strength. These fibers offer improved mechanical performance and

load-bearing capabilities, making them suitable for high-strength and durability applications. Banana and Sisal fibers enhance structural integrity, while Kithul and Palmyra fibers have lower tensile strengths, making them suitable for lighter, flexible, or improved thermal insulation applications. Understanding the tensile strength of different natural fibers enables researchers to select fibers that align with the specific mechanical requirements of the intended application, optimizing natural fiber-reinforced composites with desired strength characteristics.

4.1.5 Chemical Properties of Natural Fibers

- FTIR Test (Fourier Transform Infrared Analysis)

This technique is used to chemically characterize natural fibers. It assists in locating the chemical compounds and functional groups found in natural fibers. The FTIR spectra of natural fibers are displayed in the following figures. Between the wavelengths of 500 and 3500 cm^{-1}, Fourier Transform Infrared spectra were observed.

Figure 18 illustrates the FTIR spectra of banana fiber. Due to the presence of the hydroxyl (-OH) group in the cellulose group in fiber material, the greatest absorption peak of 3274.25 cm^{-1} was observed [110]. The banana fiber contains distributed wax material (C-H stretching), which is highlighted by the peaks at 2910.58 cm^{-1}. The peak, which was caused by the stretching of the C=O group, occurred at 1606.70 cm^{-1} and indicated the presence of hemicellulose in banana fiber [111], [100]. C=H group lignin content category is correlated with the range between 1155.40 and 1423.91 cm^{-1} [112]. The C-O groups present in the banana fiber (C-C stretching) are highlighted by the peaks at 1028.13 cm^{-1} [113].

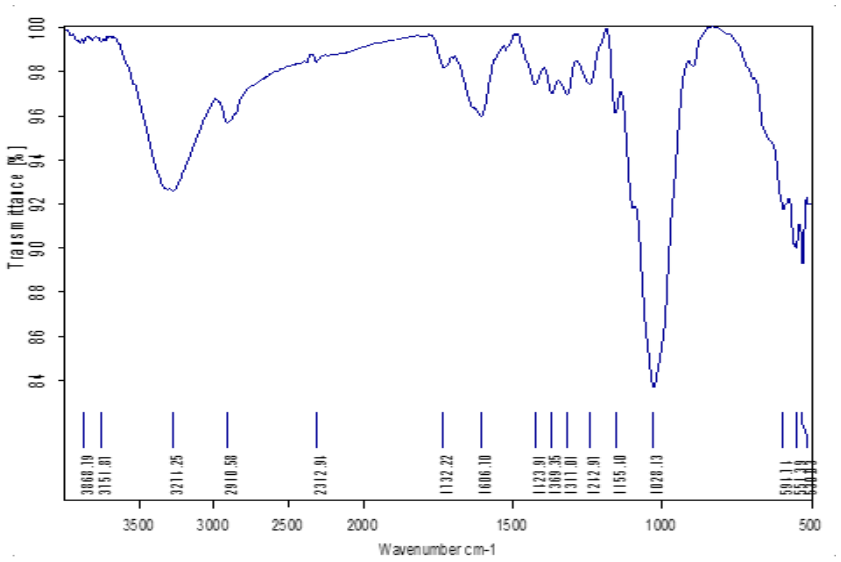


Figure 18: FTIR spectra of the banana fiber

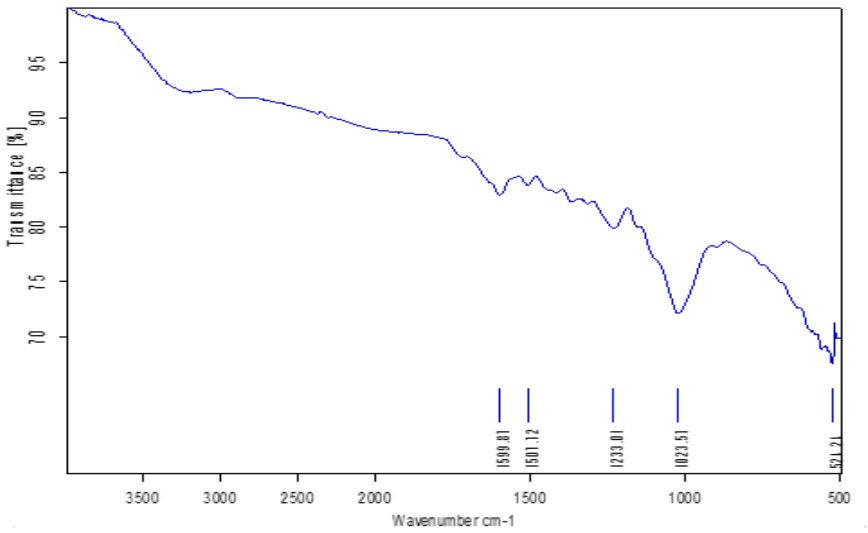


Figure 19: FTIR spectra of the coir fiber

Figure 19 displays the FTIR spectra of coir fiber. The presence of hemicellulose in the coir fiber is indicated by a peak observed at 1599.87 cm^{-1}, resulting from the stretching of the C=O group [100]. The category of lignin content for the C=H group is connected with the peak in 1233.01cm^{-1} [112]. The C-O groups present in the coir fiber (which are being stretched by C-C) are highlighted by the peaks at 1023.57 cm^{-1} [113]. After investigating the cellulose, hemicellulose, and lignin chemical structures, it will be possible to identify whether these components are present in the selected brown coir fiber.

Figure 20 shows the FTIR spectrum of Watakeiya fiber. The largest absorption peak of 3330.41cm^{-1} was noticed because the cellulose group in fiber material contains the hydroxyl (-OH) group. The peaks at 2894.90 cm^{-1} highlight the wax substance that is spread throughout the Watakeiya fiber (C-H stretching). The peak, generated by C=O group stretching, occurred between 1731.80 cm^{-1} and 1637.56 cm^{-1} and suggested the existence of hemicellulose in Watakeiya fiber. The range between 1505.73 and 1318.60 cm^{-1} is associated with the lignin content category of the C=C group. The peaks at 1240.10 cm^{-1} - 1029.80 cm^{-1} reveal the C-H groups contained in the Watakeiya fiber (C-C stretching). The C-O groups appear in the wavenumber of 1029.80cm^{-1} [113] Only the C-O stretching groups are visible in the FTIR spectrum of the kithul fiber in Figure 21. It refers to a C-O stretching bond structure found in various functional groups such as alcohol (cellulose, hemicellulose, and lignin), carboxylic acids, esters, and ethers. The FTIR spectrum of Palmyra fiber is depicted in Figure 22. In fibers made of the C-H group, the greatest absorption peak between 2920.92 cm^{-1} and 2853.12 cm^{-1} was observed. The C-O stretching group also appears in the peak value of 1012.41cm^{-1}. The peak of the sisal fiber's FTIR spectrum at 1019.06 cm^{-1} shows the presence of the C=C stretching group. Peaks ranging from 1315.34cm^{-1} to 1235.85cm^{-1} reveal C-H groups, while peak 1019.06cm^{-1} shows C-O groups in sisal fiber (Figure 23) [113].

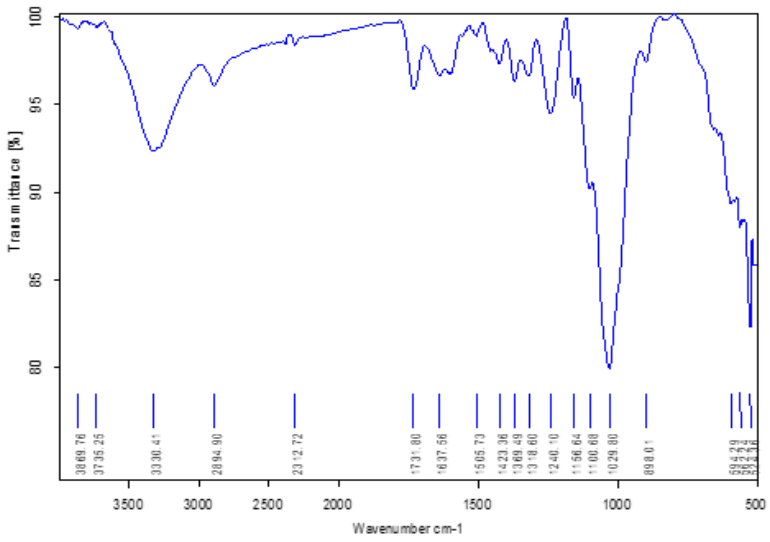


Figure 20: FTIR spectra of the Watakeiya fiber

Figure 21: FTIR spectra of the kithul fiber

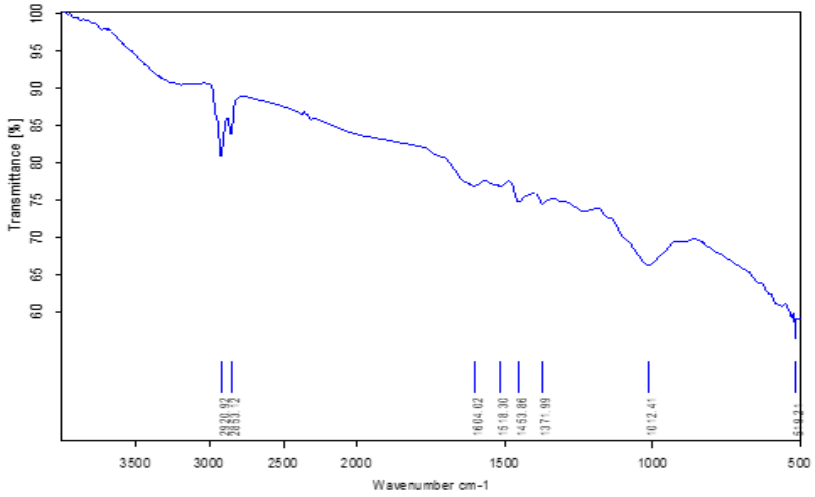


Figure 22: FTIR spectra of the Palmyra fiber

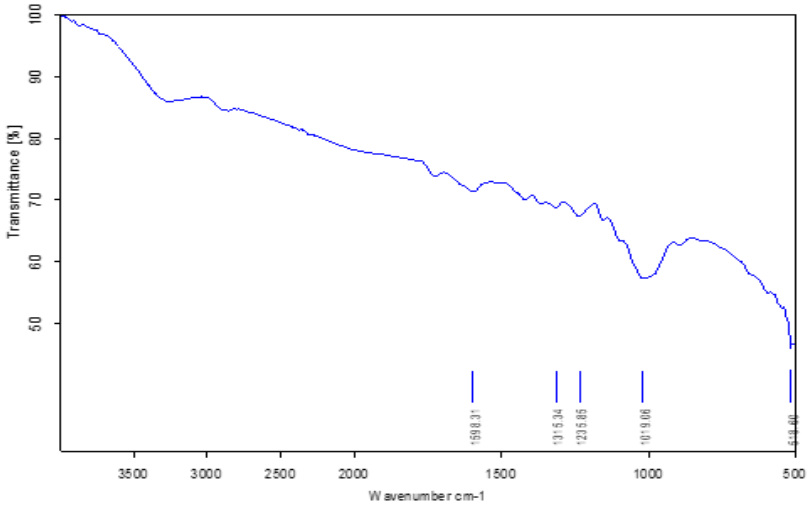


Figure 23: FTIR spectra of the Sisal fiber

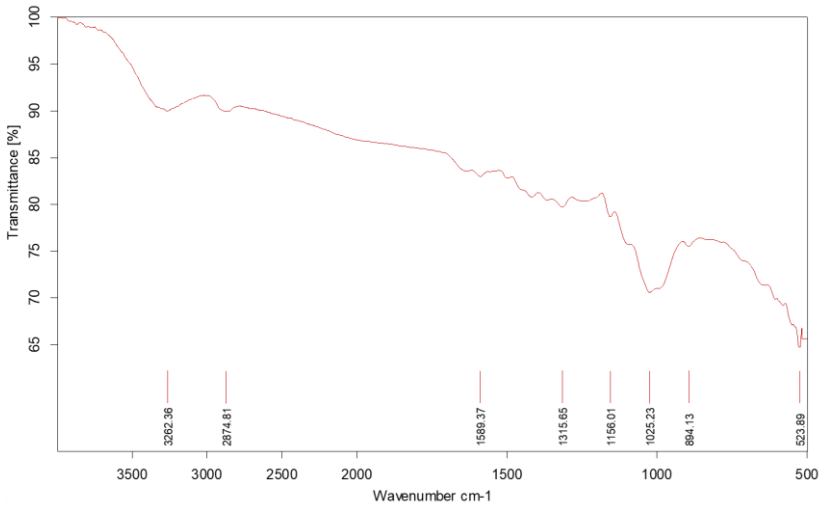


Figure 24: FTIR spectrum of a bamboo fiber sample

The FTIR spectra of bamboo fiber are depicted in Figure 24. The largest absorption peak of 3282.38cm^{-1} was noticed because the cellulose group in fiber material contains the hydroxyl (-OH) group. The bamboo fiber contains distributed wax material (C-H stretching), which is highlighted by the peaks at 2874.81 cm^{-1}. Peak ranges in the 1589.37 cm-1 to 1315.65 cm-1 range show C=H groups, whereas peaks in the 1156 cm-1 and 1025 cm-1 range show C-H and C-O groups, correspondingly.

4.1.6 Summary of Section One

The study analyzed natural fibers like Palmyra, Sisal, Bamboo, Watakeiya, Banana, and Kithul. The average diameter of these fibers was measured, and Kithul fiber had similar diameters to other fibers, suggesting its potential for use in fiber-reinforced polymer composites. The average density of Kithul fiber was 0.904g/cm^3, similar to other fibers. The study also investigated water absorption behavior, finding that Watakeiya, Sisal, and Bamboo fibers had the highest water absorption rates. Kithul fibers had a lower absorption rate, making them suitable for outdoor applications with low water absorption.

Scanning Electron Microscopy (SEM) analysis revealed that Coir, Kithul, Palmyra, and Watakeiya fibers had rough surface structures and contained impurities. Chemical treatments, such as Alkali Treatment, were applied to remove surface impurities. Kithul and Palmyra fibers exhibited lower tensile strength values than Sisal, Bamboo,

Watakeiya, and Banana fibers. The study offers valuable insights into natural fibers' water absorption behavior, surface characteristics, and mechanical properties. It underscores the potential of Kithul fibers in composite applications and identifies areas that can be further improved.

4.1.7 Chemical Properties of Selected Polyethylene Sample

- FTIR Test (Fourier Transform Infrared Analysis)

This method is employed to analyze the chemical composition of selected polyethylene samples to develop natural fiber-reinforced polymer composites. It aids in identifying the specific chemicals and functional groups present in the polyethylene sample.

An "IR spectrum" was used to calculate the infrared spectra of the chosen matrix using the Fourier transform.

The analysis was performed using an FTIR spectrometer with a resolution of 4 cm^{-1} and a scanning rate of 32 scans per minute. The analysis covered the wavenumber range of 4000 to 500 cm^{-1}.

The peaks' size and shape aid in determining the functional groups contained in polyethylene.

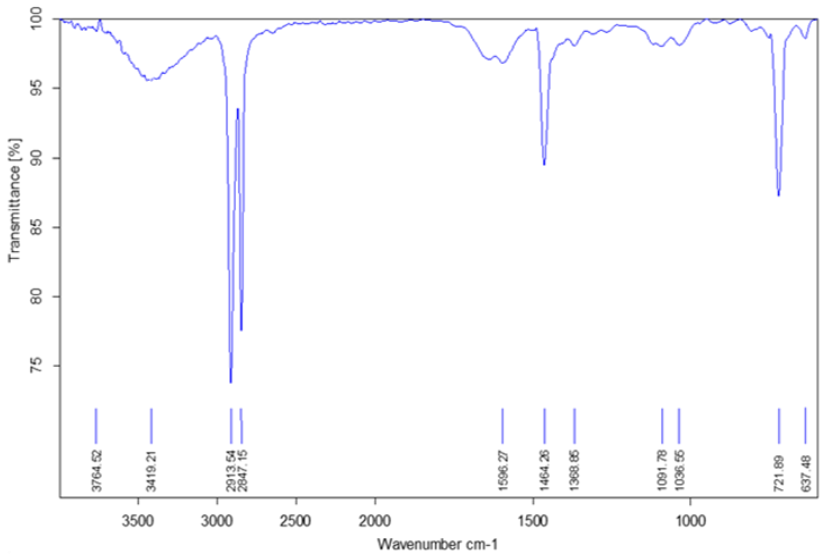


Figure 25: FTIR test for selected polyethylene sample

The stretching vibration absorption of the -CH alkane group is depicted by the peak observed in the IR spectra at the wave number range of 2913.54 - 2847.15 (Figure 25).

The extension of the polymer chain was observed due to the presence of an asymmetric -CH functional group with CH3. This is evident from the absorption peaks observed at 1596.27 and 1368.85 in the spectroscopic analysis [114].

The form of the -CH groups in the mixed section has changed, as seen by the widening of the absorption peaks in the range of 721.89 to 637.48.

Thus, the chosen material is mainly HDPE.

SECTION 02

SELECT THE OPTIMUM RATIO TO OPTIMIZE THE MECHANICAL PROPERTIES

After the HDPE and natural fiber characteristics were determined, the preparation process for the Kithul-reinforced polymer composite was started. The optimum kithul: HDPE ratio was identified as the first test in the test series. By changing the kithul fiber weight fraction, selected two materials (HDPE and Kithul fibers) were mixed into seven different ratios (0:100, 2.5:97.5, 5:95, 10:90, 20:80, 30:70, 40:60).

Ratios of 5:5 and above were not considered in the mixed thought processes. Poor bonding was apparent when the boards were manufactured, and numerous regions had hollow areas.

The tensile and bending strengths of the composite materials were accessed for the manufactured composites by changing the weight fraction of kithul to determine the optimum kithul: HDPE ratio.

4.1.8 Tensile Strength (Select the optimum ratio)

The correlation between the percentage of fiber weight and the experimental ultimate tensile strength (UTS) of reinforced composites is shown in Figure 28. According to the results, increasing the kithul fraction initially improves the composite's tensile strength. This enhancement can be due to the reinforcing properties of the kithul fibers, which improve the material's overall mechanical performance. Higher tensile strength values are obtained due to the utilization of kithul fibers, which increase strength and stiffness.

However, as the kithul fiber content continues to rise beyond a certain threshold, a decline in the ultimate tensile strength is observed. This decrease can be linked to two key factors: porosity and weak interfacial bonding within the composite.

Initially, as the kithul fiber content rises, ensuring consistent dispersion of the fibers within the composite matrix becomes increasingly tricky. This non-uniform

distribution can result in the formation of voids or pores within the material. These pores function as points of stress concentration, diminishing the composite's structural integrity and decreasing its tensile strength.

The interfacial bonding of the kithul fibers and the matrix material is also essential for load transfer and overall strength. Strong interfacial bonding becomes more challenging to provide with increased kithul fiber content. A weak connection between the fibers and the matrix reduces stress transmission and load-carrying capacity, reducing tensile strength.

To optimize the ultimate tensile strength of the composite, it is essential to find a balance between the reinforcing effect of the kithul fibers and the negative influence of porosity and weak interfacial bonding. This can be achieved through careful control of the fiber content and by implementing manufacturing techniques that minimize porosity and enhance interfacial bonding, ultimately improving the overall mechanical properties of the composite material [115].

The maximum tensile strength can be observed when the kithul fiber content is 10% (10%:90% Kithul: Polyethylene ratio) and 15.45 N/mm^2.

In their research conducted in 2021, Dharmaratne et al. examined the impact of different coir weight fractions on the tensile strength of composites. Their findings revealed that the maximum tensile strength of 6.75 mpa is achieved when the coir weight fraction ranges between 20% and 30% of the total weight [97].

Another study [116] was conducted to determine the tensile properties of a composite comprised of HDPE and banana fiber. In this study, banana fiber composites were utilized, employing two distinct fiber orientations: continuously bidirectional and continuously aligned. According to these two scenarios, the highest tensile strength (55.7 mpa for continuously aligned fiber and 22.6 mpa for continuously bidirectional fiber) occurs when the banana weight fraction is 20% of the total weight.

In 1999, Joseph conducted a study [117], to investigate the tensile characteristics of sisal fiber-reinforced polypropylene (PP), polystyrene (PS), and low-density

polyethylene (LDPE) composites with longitudinally and randomly oriented 6mm lengths. Results show that the tensile strength and modulus increase for PP-sisal, PS-sisal, and LDPE-sisal composites as the fiber content increases from 0 to 30%, while the highest ultimate tensile values (PP with sisal - 44.40Mpa, PS with sisal - 45.06mpa, and LDPE with sisal - 31.12mpa) indicate a 30% weight fraction of fiber in total.

It suggests that the type of fiber will have a considerable impact on tensile strength [118].

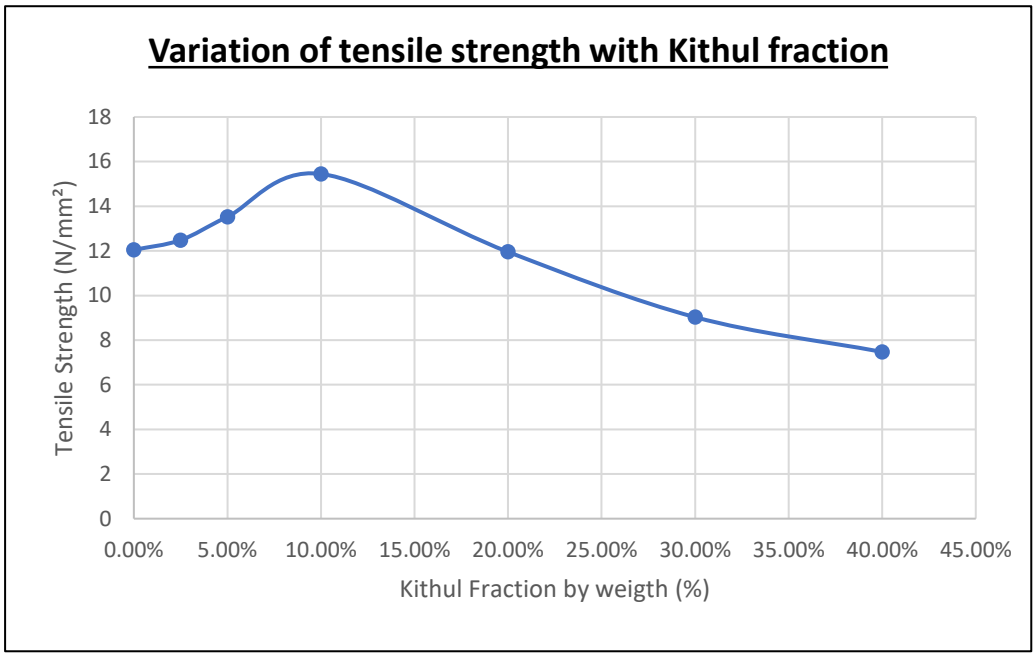


Figure 26: Variation of tensile strength with kithul fraction

Standard Deviation

Calculate the Mean (Average):

Mean ($\ddot{X}$) = (12.044 + 12.483 + 13.525 + 15.45 + 11.9551 + 9.03 + 7.472) / 7 ≈ 11.6448

Calculate the Deviation from the Mean for each data point:

Deviation from Mean = Value – Mean

- For 12.044: 12.044 - 11.6448 ≈ 0.3992
- For 12.483: 12.483 - 11.6448 ≈ 0.8382
- For 13.525: 13.525 - 11.6448 ≈ 1.8802

- For 15.45: 15.45 - 11.6448 ≈ 3.8052
- For 11.9551: 11.9551 - 11.6448 ≈ 0.3103
- For 9.03: 9.03 - 11.6448 ≈ -2.6148
- For 7.472: 7.472 - 11.6448 ≈ -4.1728

Square each Deviation:

Squared Deviation = (Deviation from Mean)^2

- $(0.3992)^2 \approx 0.1594$
- $(0.8382)^2 \approx 0.7016$
- $(1.8802)^2 \approx 3.5298$
- $(3.8052)^2 \approx 14.4941$
- $(0.3103)^2 \approx 0.0962$
- $(-2.6148)^2 \approx 6.8414$
- $(-4.1728)^2 \approx 17.4206$

Calculate the Mean of Squared Deviations:

Mean of Squared Deviations = (0.1594 + 0.7016 + 3.5298 + 14.4941 + 0.0962 + 6.8414 + 17.4206) / 6 ≈ 5.9425

Calculate the Standard Deviation (σ):

Standard Deviation (σ) = 2.6831

The calculated standard deviation of 2.0513 indicates that the tensile strength values are moderately variable around the Mean (average) tensile strength of 11.645. This implies that while the material's tensile strength is relatively consistent on average, there is still some variability in individual measurements. In practice, this means that the material's tensile strength can deviate from the average by around 2.0513 units, which is useful information for quality control and product specifications.

Understanding the standard deviation is essential for making informed decisions in various applications, such as manufacturing and engineering. It measures the data's reliability and predictability, assisting professionals in determining whether the material's tensile strength meets desired standards and making necessary adjustments

or improvements. In conclusion, a standard deviation of 2.0513 in this context indicates a moderate variation in composite tensile strength measurements, which is valuable data for quality assessment and decision-making processes.

4.1.9 Flexural Strength (Select the optimum ratio)

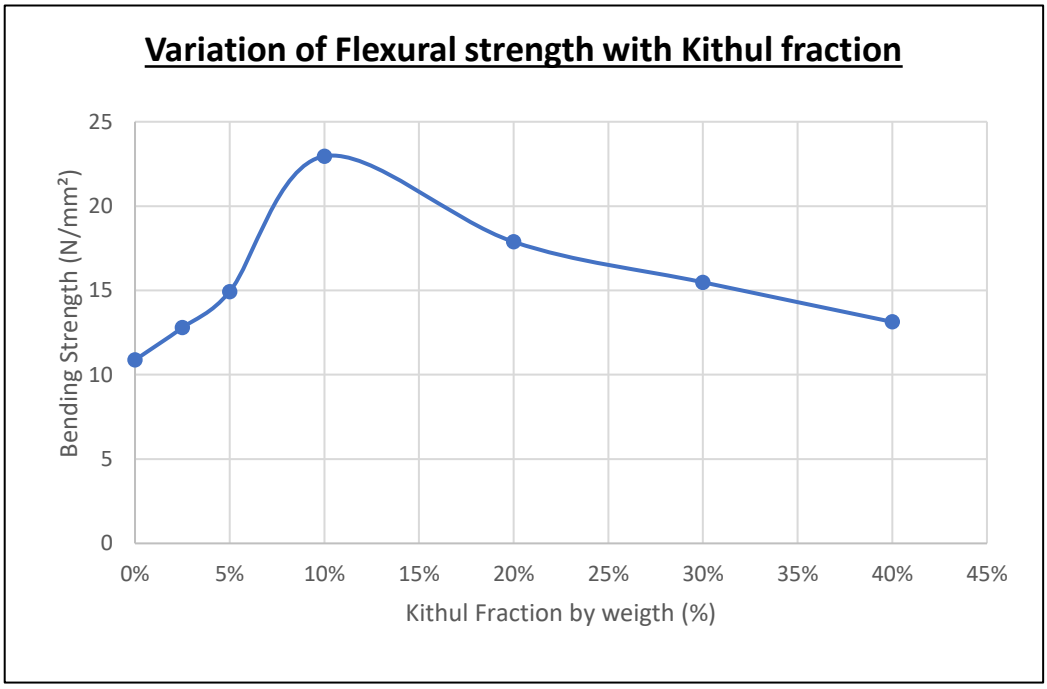


Figure 27: Variation of flexural strength with kithul fraction

Figure 29 illustrates the variation in flexural strength as a function of the kithul fraction by weight. With an increase in the kithul fiber content, there is a decline in the flexural strength of the composite. Factors contributing to this decline include matrix-fiber incompatibility, inefficient production processes, fiber deterioration, and other factors. Matrix-fiber incompatibility is crucial for interfacial solid bonding and efficient load transfer, while inefficient production processes can affect the composite's mechanical properties. Fiber deterioration can result from overloading or environmental factors, reducing reinforcement efficiency and declining flexural strength. Other factors influencing the decline in composite strength include improper fiber alignment, defects or voids, and inadequate fiber length or aspect ratio. To optimize the flexural strength of the composite, it is essential to address these issues by ensuring proper matrix-fiber compatibility, optimizing production processes, selecting appropriate fiber treatment methods, and maintaining fiber quality [119].

The research paper titled "Mechanical Characteristics of Natural Fiber-Reinforced Polymer Composites (Kenaf, Oil Palm Empty Fruit Bunch)," published in 2014 concluded that the PLA-EFB (Polylactic Acid 3051D with palm empty fruit bunch

fiber) and PLA-KE (Polylactic Acid 3051D with Kenaf) composites exhibited optimal flexural strength at a fiber loading of 40%. The reported values for PLA-EFB and PLA-KE composites were 169.8 MPa and 209.2 MPa, respectively. Within this study, the flexural strengths of polymer composites reinforced with natural fibers exhibited an upward trend as the fiber content was raised. The flexural strength peaked at a 40% fiber loading; however, it declined when the fiber content was further increased to 60%. According to the author of this study, the decrease in flexural strength at 60% fiber content can be related to inadequate matrix dispersion because of the excessive loading of the fibers, which tend to accumulate in the composite. PS composites demonstrate superior flexural strength compared to EFB (palm empty fruit bunch fiber) reinforcement. PS composites demonstrate the highest flexural strength at a 40% fiber loading, reaching 50.5 MPa. This is followed by 20% fiber loading at 47.6 MPa and 60% at 27.8 MPa. Similarly, PS-KE (polystyrene with Kenaf) composites exhibit the highest flexural strength at 40% fiber loading [120].

Dharmaratne et al.'s 2021 study revealed that coir fiber-reinforced composites exhibit flexural characteristics of 29.85 N/mm2 when the weight fraction of coir is 25% [97]. According to research by Kumar et al. (2014), the composite with treated 4mm Kenaf fiber has the maximum flexural strength, measuring 166.2N/mm². The composite with 8mm untreated Kenaf fiber showed a flexural strength of 139.5 N/mm² [121].

It also suggests that the type of fiber will have a considerable impact on flexural strength [118].

Standard Deviation

Calculate the Mean (Average):

Mean ($\ddot{X}$) = (10.875 + 12.789 + 14.929 + 22.959 + 17.878 + 15.481 + 13.133) / 7 ≈ 15.435

Calculate the Deviation from the Mean for each data point:

Deviation from Mean = Value – Mean

- For 10.875: 10.875 - 15.151 ≈ -4.276
- For 12.789: 12.789 - 15.151 ≈ -2.362
- For 14.929: 14.929 - 15.151 ≈ -0.222
- For 22.959: 22.959 - 15.151 ≈ 7.808
- For 17.878: 17.878 - 15.151 ≈ 2.727
- For 15.481: 15.481 - 15.151 ≈ 0.330
- For 13.133: 13.133 - 15.151 ≈ -2.018

Square each Deviation:

Squared Deviation = (Deviation from Mean)^2

- (-4.276)^2 ≈ 18.289
- (-2.362)^2 ≈ 5.590
- (-0.222)^2 ≈ 0.049
- (7.808)^2 ≈ 61.054
- (2.727)^2 ≈ 7.446
- (0.330)^2 ≈ 0.109
- (-2.018)^2 ≈ 4.074

Calculate the Mean of Squared Deviations:

Mean of Squared Deviations = (18.289 + 5.590 + 0.049 + 61.054 + 7.446 + 0.109 + 4.074) / 6 ≈ 13.4622

Calculate the Standard Deviation (σ):

Standard Deviation (σ) = 3.9986

The calculated standard deviation of 3.9986 reveals essential information about the composite flexural strength measurements. It indicates that the flexural strength values vary moderately around the Mean (average) flexural strength of approximately 15.435. This means that while the material's flexural strength tends to be around 15.435, there are positive and negative deviations extending to an average of about 3.9986 units from this Mean.

These findings have important implications for materials engineering and construction applications. First and foremost, they provide valuable information for quality control

and product evaluation. The standard deviation indicates the degree to which the flexural strength measurements deviate from the expected average. In practice, this means that the flexural strength of the composite material can vary within a range of about 3.9986 units.

Engineers and quality assurance specialists need this information to decide on material choice, structural design, and manufacturing procedures. It enables them to determine whether the flexural strength values meet desired standards and whether additional measures or adjustments are required to ensure structural integrity and reliability in construction or other applications.

SELECT THE OPTIMUM TEMPERATURE/ PRESSURE TO OPTIMIZE THE MECHANICAL PROPERTIES

- Select the optimum temperature

To determine the optimal temperature to create composites, composite boards were prepared using the indicated kithul weight percentage of 10% of the total weight while adjusting the processing temperature.

The temperatures were chosen based on the melting temperature of HDPE. HDPE generally has a melting point between 120°C and 180°C (248°F and 356°F), with an average melting value of 130°C (266°F) [122]. However, the produced composites showed poor bonding in the temperature range of 120°C to 140°C, as indicated in the figure. Because a composite material's processing temperature is influenced by the fiber, its volume percentage, its orientation, and the direction in which heat is transferred, in addition to the type of polymer [123]. As a result, processing temperatures were rising above the polymer's melting point.

Consequently, six temperatures in the range of 145°C –170°C were chosen to produce composite boards.

Figure 28: Prepared composite boards with improper bonding

4.1.10 Tensile Strength (Select the optimum temperature)

Figure 31 shows a graphic representation of the relationship between the tensile strength of the composite board and temperature.

According to the findings, tensile strength increases as temperature rises to 150 °C. The maximum tensile strength can be observed as 17.41mpa. The experiments then reveal that the ultimate tensile strength decreases further as the temperatures increase. Increasing the temperature of composites also aids in lowering the water content of the fiber. The results of the composite material produced by heating the fiber from an increased processing temperature produce the best strength [28]. However, increasing the temperature caused the kithul composite to behave like a viscous material, resulting in energy loss. This also led to a higher tension being needed to break the bonding of the material, which decreased its storage modulus [124].

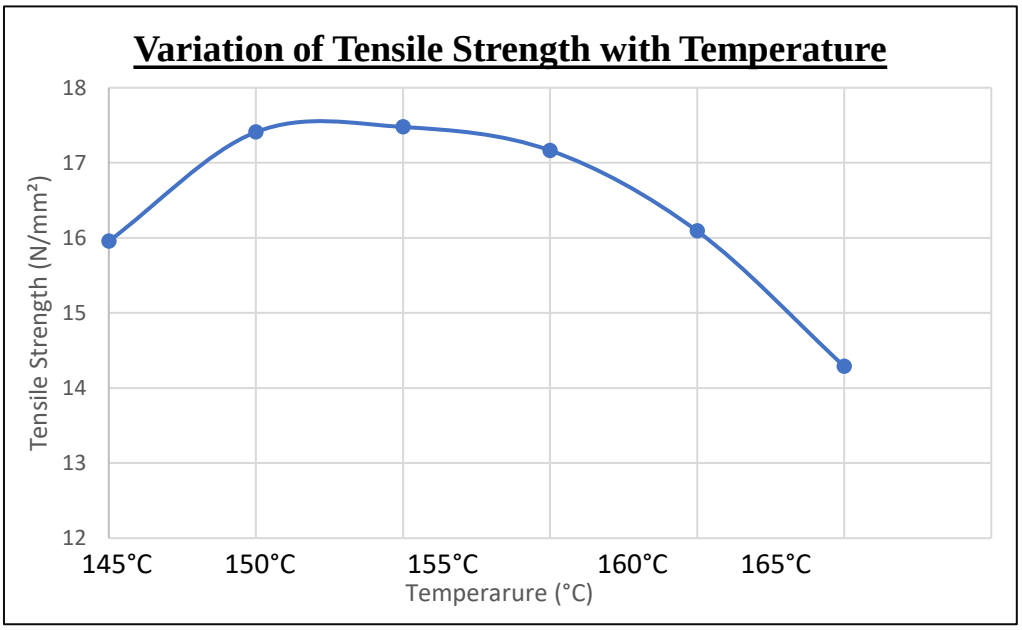


Figure 29: Variation of tensile strength with composite processing temperature

Standard Deviation

$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(X-\ddot{X})^2}{N-1}} = 1.2257$$

For the composite tensile strength data set, the calculated standard deviation is approximately 1.2257. This value represents the spread or variability in tensile strength measurements as a function of temperature variation.

The results show that the tensile strength values have a relatively low level of variability around the mean (average) tensile strength of 16.398. This means that the tensile strength of the material is typically close to the mean value, with deviations less than 1.2257 units in either direction.

These findings are critical in determining how the material behaves at various temperatures. The low standard deviation indicates that the composite tensile strength is relatively consistent, with only minor fluctuations due to temperature changes. This consistency is useful in applications where the mechanical properties of the material must remain stable over a wide temperature range.

In practice, a low standard deviation indicates that the material can be relied on to maintain its tensile strength within a predictable range, which is especially important in engineering and manufacturing contexts where consistency is critical.

4.1.11 Flexural Strength (Select the optimum temperature)

Figure 32 illustrates the variations in flexural strength as a function of the composite processing temperature. With an elevation in temperature, the flexural strength exhibits an increase while maintaining the same tensile strength. However, as the temperature continues to rise, the flexural strength eventually starts to decline. The maximum flexural strength of 16.389 MPa occurs when the composite processing temperature is 150°C.

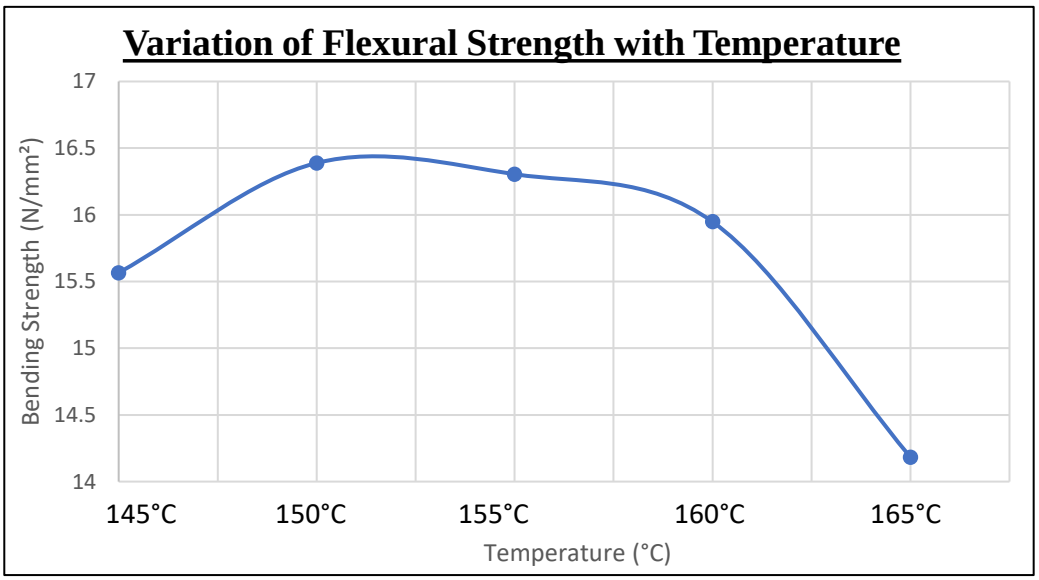


Figure 30: Variation of flexural strength with temperature

The study of "High-density polyethylene composite reinforced with natural fibers and hybridized with ultra-high molecular weight polyethylene" in 2019, indicates that the optimum processing temperature for kenaf fiber with HDPE is between 135°C and 145°C [125].

The optimal processing temperature for hemp fiber with LDPE is 140°C, according to a 2011 study by Asim Shahzad [126].

Research done in 2021 by S.M. Shahabaz, indicates 135 °C is the optimum temperature for kenaf and LDPE composite material [127].

When compared to previous research and the current study, it can be determined that fiber type and polymer type have an impact on the temperature at which composites are processed.

When the temperature is increased, the behavior of the kithul composite changes, and it starts to exhibit viscous properties. This means that the material becomes less resistant to deformation and experiences energy loss during loading. Consequently, the composite's storage modulus declines, while the temperature rise impacts the intermolecular interactions within the composite. With higher temperatures, both the matrix material (polyethylene) and the kithul fibers exhibit increased molecular mobility. This heightened mobility disrupts the bonding between the matrix and fibers, resulting in a reduction in the storage modulus. Additionally, the elevated temperature weakens the interfacial bonding between the fibers and matrix. The weakened bonding reduces the load transfer efficiency, and more tension is required to break the bonding and cause failure in the material. The decrease in storage modulus indicates a decrease in the stiffness and rigidity of the composite. The vicious behavior and energy loss observed at higher temperatures can negatively impact the mechanical performance of the composite, making it less suitable for applications requiring high stiffness and strength.

The Mechanical properties are maximized when the temperature is 150°C. To prepare the composite for further research, 150 °C was chosen as the temperature.

Standard Deviation

$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(X-\ddot{X})^2}{N-1}} = 0.8971$$

The composite flexural strength data set shows a low standard deviation of 0.8971, indicating consistent flexural strength values around the mean value of 15.6782. This low variability is crucial for assessing the material's behavior under changing temperature conditions, as it indicates minimal fluctuations due to temperature variations. This consistency is essential for engineering and manufacturing applications, as it ensures consistent performance under varying thermal conditions.

- Select the optimum pressure

To find the optimum pressure for creating composites, composite boards were created using a predetermined kithul weight proportion of 10% of total weight and 150°C of composite processing temperature while modifying the processing pressure.

Improved the matrix and the fiber necessity form an interfacial bond with significant compression pressure. The research indicates that for composite materials made of natural fibers, pressure ranges from 20 to 690 tones. It is dependent on the material whether to use one pressure or another, so it must be managed because this factor directly influences the mechanical characteristics of the finished product [128].

Processing pressure in this research changed from 20 tons to 40 tons. To determine the optimum pressure to produce composite materials, five processing pressures were tested.

4.1.12 Tensile Strength (Select the optimum pressure)

The resulting composites' tensile strength measured 11.36 MPa at a pressure of 30 tons, which is the optimum pressure. Following the application of pressures of more than 30 tons, a reduction in tensile strength is shown in Figure 33. Increased pressure resulted in improvements in density, ultimate tensile strength, and Young's modulus [129]. The use of high pressure during the production of natural fiber-reinforced polymer composites can lead the polymer matrix to melt. The composite boards can acquire hollow areas or voids as a result of this melting.

When processing composite materials, the use of high pressure is frequently required to achieve adequate compaction and consolidation of the materials. However, if the pressure is too high or the temperature is above the melting point of the polymer matrix, the polymer can melt.

When the polymer melts, it can flow away from certain areas, leaving behind empty spaces or voids within the composite structure. These hollow areas can be detrimental to the mechanical properties and structural integrity of the composite boards. They act

as stress concentration points, reducing the overall strength and stiffness of the material. Moreover, the presence of voids can also lead to dimensional instability and decreased durability of the composite.

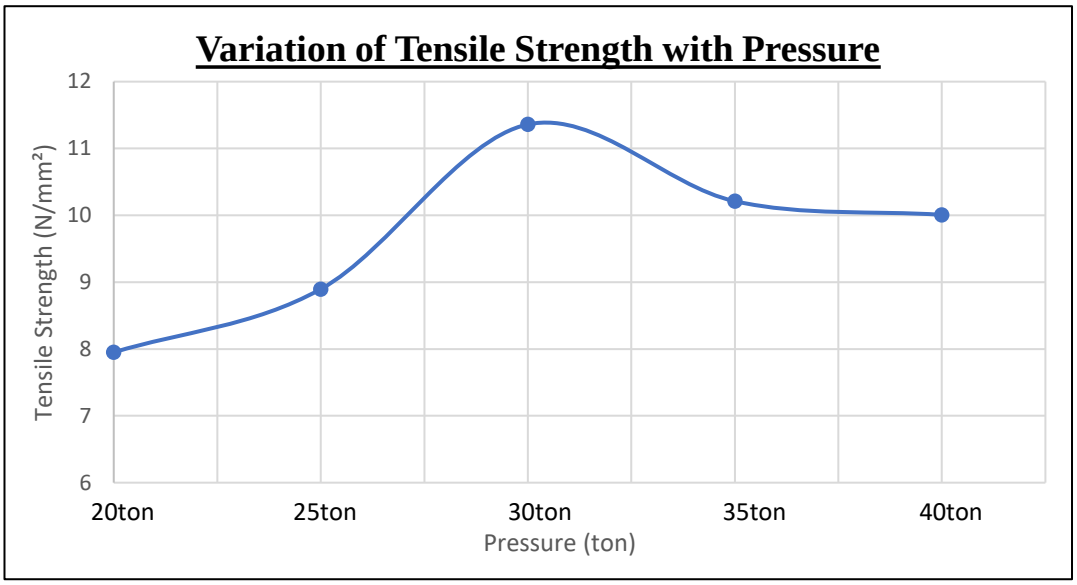


Figure 31: Variation of tensile strength with pressure

Standard Deviation

$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(X-\ddot{X})^2}{N-1}} = 1.3053$$

The composite tensile strength data set shows a moderate level of variability around the mean value of 9.6848, with deviations typically less than 1.3053 units in either direction. This indicates that the material's tensile strength remains reasonably consistent, with some fluctuations due to pressure variations. This level of consistency is crucial in engineering and manufacturing applications where the material's mechanical properties must remain stable even under varying pressures. In practical terms, the moderate standard deviation indicates that the material can generally maintain its tensile strength within a predictable range, crucial for designing components and structures.

4.1.13 Flexural Strength (Select the optimum pressure)

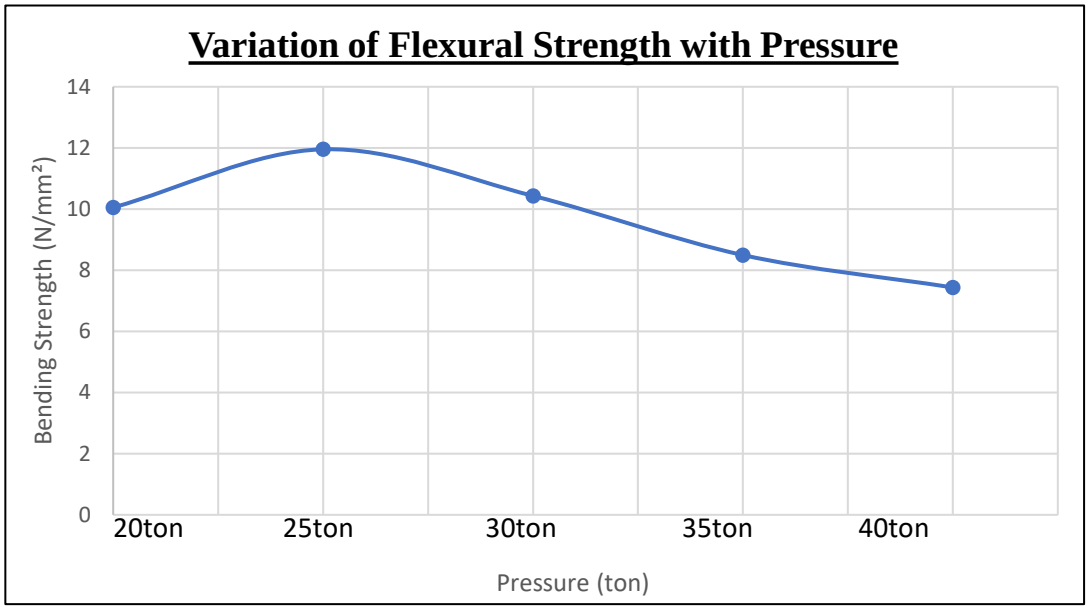


Figure 32: Variation of flexural strength with pressure

The fluctuation in flexural strength as a result of composite processing pressure is shown in Figure 34. The results of the optimum pressure in this situation are 25 tons of pressure at 11.995 MPa.

According to C. Elanchezhian et al.'s (2018) study, sisal fiber and polymer composites' maximal tensile and flexural characteristics were demonstrated at 4.2Mpa of pressure [130].

The study “Review and Evaluation of Recent Developments and Proposed Future Directions in Coir Fiber Reinforced Green Polymer Composites” in 2015 shows the optimum pressure for developing coir fiber with polymer composites was 3.5Mpa [114].

Tensile strength and bending strength are both maximum at 30 tons and 25 tons, respectively, in terms of mechanical properties. In this case, taking into account both values, 30 tons were selected. Because of this, the ultimate tensile strength of the material under 25 tons of pressure is 8.896 MPa, while that of material under 30 tons is 11.36 MPa. However, the ultimate flexural strength test indicates values of

11.955 MPa and 10.432 MPa for 25 tones and 30 tones, respectively. Because the ultimate tensile strength test at 25 tons of pressure produced a value of 8.896 MPa. This is less than 10432mpa, the pressure at which the ultimate flexural strength of 30 tones is measured. Consequently, the choice of 25 tones results in the production of low tensile strength.

Standard Deviation

$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(X-\ddot{X})^2}{N-1}} = 1.7548$$

The composite flexural strength data set shows a moderate level of variability around the mean value of 9.6742, with deviations typically less than 1.7548 units in either direction. This indicates that the material's flexural strength remains reasonably consistent, with some fluctuations due to pressure variations. This level of consistency is crucial in engineering and manufacturing applications where the material's mechanical properties must remain stable even under varying pressures. In practical terms, the moderate standard deviation indicates that the material can generally maintain its flexural strength within a predictable range, which is essential for designing components and structures.

SELECT A SUITABLE LENGTH OF FIBER TO OPTIMIZE THE MECHANICAL PROPERTIES

Following the choice of the kithul weight fraction, processing pressure, and temperature, the kithul fiber length was varied to find the suitable kithul fiber length for developing composite boards. In this case, six different samples were developed by changing the kithul length. The chosen lengths are 5mm, 10mm, 15mm, 20mm, 25mm, and 30mm. Fiber lengths greater than 30 mm were not taken into consideration. Because the probability of fiber disorientation and even aggregation increases as fiber length increases. The long-fiber reinforced composite's tensile and flexural strengths were consequently assumed to be lower than those of the short-fiber reinforced composite [131].

4.1.14 Tensile Strength (Select the fiber length)

The experimental ultimate tensile strength (UTS) of the reinforced composites is affected by increasing fiber length, as shown in Figure 35. The findings demonstrate that as the length of the kithul fiber increases, tensile strength also rises; however, when the kithul fiber length extends further, the values start to decline. Here, the highest tensile strength is realized when the kithul fiber length is 15mm and it is 12.258 N/mm^2.

The initial increase in tensile strength with increasing fiber length can be attributed to the improved load transfer and reinforcement effect provided by longer fibers. Longer fibers have a greater surface area for interaction with the matrix material, enhancing stress transfer and overall strength.

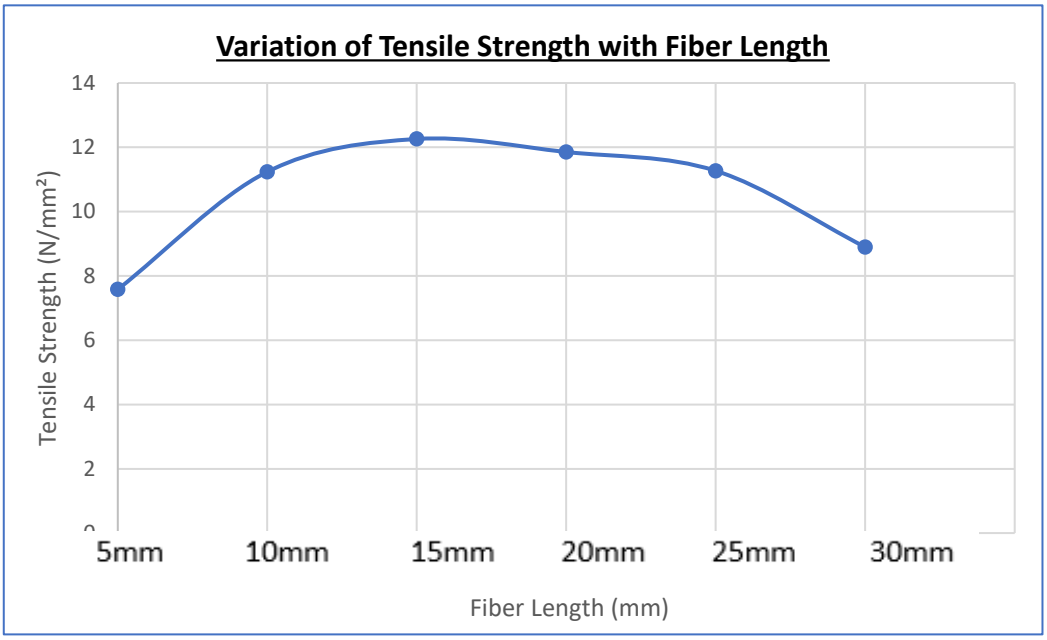


Figure 33: Variation of tensile strength with fiber length

However, as the fiber length continues to increase beyond an optimal point, several factors can contribute to the subsequent decrease in tensile strength:

1. Fiber entanglement or clustering: Excessive fiber length can lead to fiber entanglement or clustering within the composite. This can result in poor fiber dispersion, leading to local stress concentrations and reduced mechanical properties.
2. Inefficient fiber-matrix bonding: Longer fibers may have reduced contact with the matrix material, resulting in weaker interfacial bonding. Weak fiber-matrix bonding can hinder load transfer and lead to premature fiber pullout, decreasing the overall tensile strength.
3. Fiber alignment issues: Longer fibers can be more challenging to align uniformly within the matrix. Poor fiber alignment can cause variations in stress distribution and contribute to weaker mechanical properties.

To optimize the tensile strength of the composite, it is important to find the appropriate fiber length that balances reinforcement and interfacial bonding. This can be achieved through careful fiber length selection, optimization of processing parameters, and ensuring proper fiber dispersion and alignment within the matrix material.

Amuthakkannan et al.'s 2013 study on the impact of the tensile strength of composites with several different Basalt fiber lengths found that the maximum tensile occurs when the fiber length is 4 mm. According to the author, composites with shorter fiber lengths (4mm) have lower tensile strengths than composites reinforced with 10mm fiber. Because of the incorrect connection between the fibers and the matrix, shorter fibers may not be compatible with composites [132].

Another investigation [133] was carried out to find out the tensile characteristics of polyester composites reinforced with sisal, banana, and sun hemp fibers. The specified composites with 30 mm fiber lengths gradually increase in tensile strength as the fiber weight ratio increases up to a specific value. Tensile strength has decreased as a result of further increases in the fiber length and fiber weight ratio.

H. Ranganna et al. Investigated the variation in the sisal-glass hybrid composites' compressive, flexural, and tensile strengths [134]. Comparing hybrid composites with fiber lengths of 1 and 3 cm, they observed that composites with 2 cm fiber lengths had the highest tensile, flexural, and compressive strengths.

The average length of most natural fibers is between 10mm and 30mm. Low tensile properties are caused by increasing fiber percentages below the fiber length of 10mm, and incorrect matrix material bonding over the fiber length of 30mm also results in low tensile properties.

Standard Deviation

$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(X-\ddot{X})^2}{N-1}} = 1.852$$

The composite tensile strength data set shows moderate variability around the mean value of 10.5155, with deviations typically less than 1.852 units. This indicates that the material's tensile strength remains consistent, with some fluctuations due to fiber length variations. This consistency is crucial for designing products and structures that need to perform consistently in situations where kithul fiber length may vary.

4.1.15 Flexural Strength (Select the fiber length)

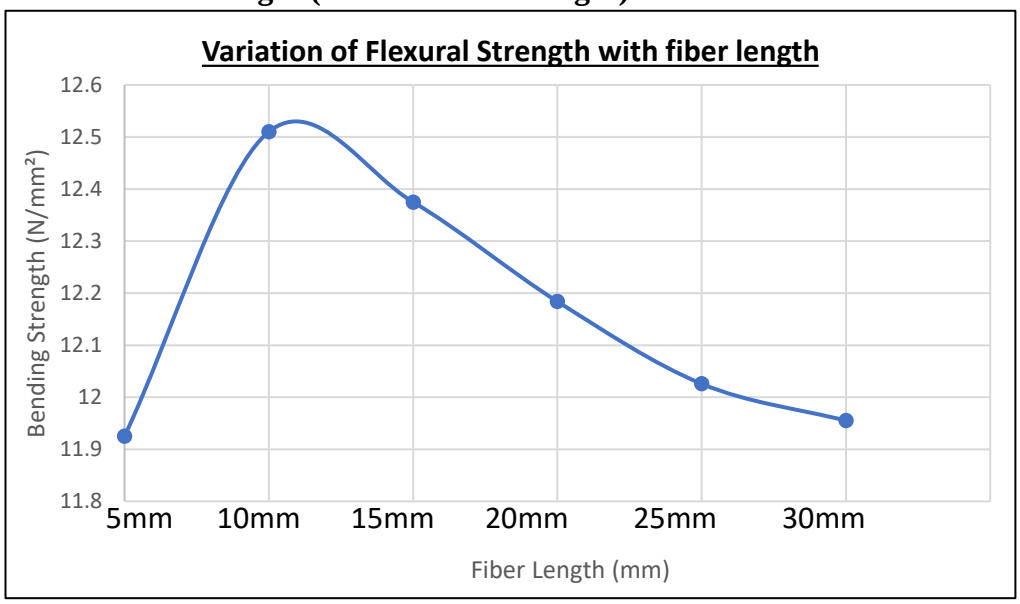


Figure 34: Flexural strength varies with fiber length

The experimental flexural strength of the reinforced composites changes with increasing fiber length, as depicted in Figure 36. The findings illustrate that when kithul fiber length increases, flexural strength increases as well, and as kithul fiber length increases further, the values start to decrease. Here, the kithul fiber length is 10 mm, and the maximum flexural strength is 12.51 N/mm2.

According to research done in 2013 by Amuthakkannan et al., composites with several different Basalt fiber lengths had their maximum flexural strength estimated. The flexural modulus of basalt fiber-reinforced polymer composites was examined in this study using a three-point load. The flexural modulus of the 10 mm length of fiber indicated better properties than the 4 mm length of fiber when comparing the two lengths of fiber [132].

Another study published in 2022 on Silane-Treated Pineapple Leaf Fiber Reinforced Polymer Composites shows that the 20 mm length of PALF (Silane-Treated Pineapple Leaf Fiber) exhibited enhanced characteristics especially flexural strength, which is connected to fiber-matrix interfacial bonding [135].

The kithul fiber length of 15mm in tensile and 10mm in bending strength yields the best mechanical properties. However, in this situation, fiber composite with lengths of 10mm and 15mm show the highest bending strength than tensile strength. As a result, choose the fiber length with the highest value of bending strength when choosing fiber length.

Standard Variation

$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(X-\ddot{X})^2}{N-1}} = 0.244$$

The composite flexural strength data set shows a low standard deviation (σ) of approximately 0.244, indicating minimal variability around the mean value of 12.179. This indicates that the material's flexural strength tends to vary slightly around this mean value, with deviations typically less than 0.244 units in either direction. This low standard deviation is crucial for evaluating how variations in kithul fiber length impact the material's flexural properties, as it suggests the material maintains its flexural strength within a predictable range, which is essential for designing products and structures that need to perform consistently.

IMPACT STRENGTH, WATER ABSORPTION, THICKNESS SWELLING, AND FLAMMABILITY TEST

To obtain the best tensile and flexural characteristics, composites were made utilizing the chosen kithul fiber weight fraction, processing temperature, pressure, and kithul fiber length. To ascertain the final result of the creation of composite boards, these prepared composites were tested for impact resistance, water absorption, and flammability.

4.1.16 Impact Strength

The impact test is carried out in a Charpy impact setup following ASTM: D256 standard (Figure 37)). The samples are shown in Figure 38. Before initiating the swinging motion until a fracture occurs, the test apparatus needs to be loaded with the specimen [136]. The impact test is utilized to determine the energy required for the material to fracture.

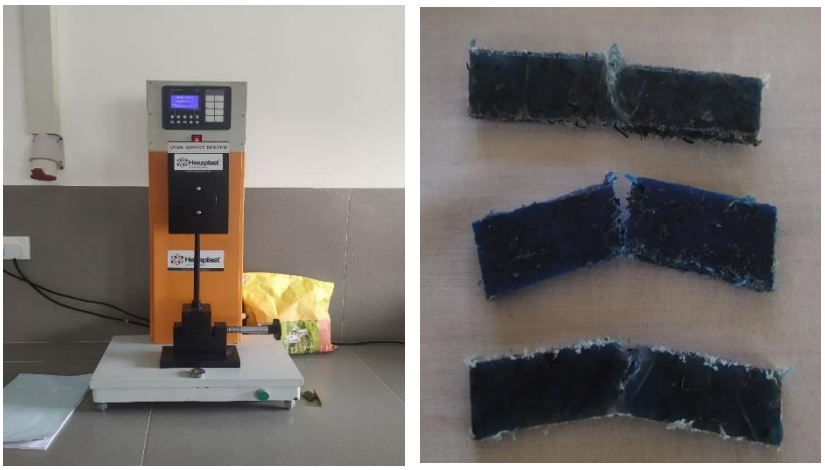


Figure 35: Cantilever Beam (Izod –Type) Impact Machine and Prepared samples

The energy lost during impact is the energy that the specimen absorbs. Table 14 lists the energy absorption ratings for several laminates. Three samples were evaluated to provide an average value of the impact strength.

Table 14: Composite Impact Strength

Sample Number	Impact Strength (Joule/Meter)
1	70
2	70
3	60
Average	66.67

In 2016, Sanjay et al. conducted a study examining the mechanical properties of polyester composites reinforced with banana and E-glass textiles. The objective of their research was to enhance the favorable mechanical characteristics of a fiber created by combining banana and E-glass materials. Testing is done to determine part of the impact resistance of natural fiber. Results indicate that pure glass laminate has the highest impact strength, whereas pure banana laminate has the lowest. The impact strength ranges from 1 J/m to 6 J/m, accordingly [136].

Wambua et al. investigated the substitution of glass fibers with natural fibers. The various natural fiber composites' mechanical characteristics were evaluated and compared the study demonstrated a positive correlation between the weight percentage of kenaf reinforcement and the impact strength of polypropylene composites, reaching 54 kj/m². Despite exhibiting comparatively lower mechanical properties, coir fiber composites displayed superior impact strength compared to both jute and kenaf composites [137].

Oksman et al. studied the mechanical characteristics of thermoplastics reinforced with natural fiber mats. This research is focused on a Flax fiber with polypropylene to enhance the desired mechanical properties. To determine some of the impact strength of produced composites, an impact strength test is undertaken. The highest impact strength, according to the results, was 751J/m [138].

Depending on variables including the type of fibers utilized, the matrix material used, the quality of the fiber-matrix interface, and the manufacturing technique used, the impact strength of natural fiber-reinforced composites varies significantly. Natural fibers have lower specific strength and stiffness compared to synthetic fibers but exhibit good impact resistance due to their energy absorption and distribution. Their inherent toughness and microstructure contribute to their impact resistance. The impact strength values of composites reinforced with natural fibers exhibit notable variations based on the interplay of different factors, including the choice of fibers, matrix materials, processing techniques, and testing methodologies. To obtain accurate and up-to-date impact strength values, research studies or consult experts in the field. According to previous literature and observed results, it can determine when modifications to the matrix substance and fiber type may considerably affect the impact strength of composite materials.

4.1.17 Water Absorption

Due to the importance of water absorption characteristics to natural fiber-reinforced composites, they have been created for this investigation. This test was performed on the HDPE composite kithul to evaluate one of its crucial physical characteristics: the amount of water absorbed under specific settings and periods. Factors such as void/pore structure, humidity, temperature, fiber volume percentage, and matrix viscosity contribute to the dispersion of moisture in the composite material [139].

Assessing the performance of natural fiber-reinforced composites involves a critical consideration of water absorption, as it has a substantial influence on their mechanical properties, dimensional stability, and long-term durability. Natural fibers have hydrophilic characteristics that absorb moisture from their surroundings. The water absorption characteristics of these composites are influenced by various factors including the amount and type of fibers, fiber treatment, matrix material, processing parameters, and surface modifications or coatings. The porosity and surface morphology of the fibers also play a role in determining water absorption. High water absorption can cause dimensional changes, compromised structural integrity, and

degradation of the fiber-matrix interface, promoting fiber de-bonding and reduced overall performance.

To mitigate water absorption, surface treatments, selecting a hydrophobic or water-resistant matrix material, and proper manufacturing techniques can help reduce the composite's porosity and limit water ingress. The water absorption characteristics of composites reinforced with natural fibers can exhibit significant variations based on the interplay between different factors such as fiber types, matrix materials, processing methods, and testing conditions. It is essential to consult relevant research studies or experts for accurate information on the water absorption characteristics of prepared composites.

To determine the location of excessive water absorption, two test series were carried out. Figure 39 shows the levels of water absorption for the created composites in test series one for both of the exposed samples' two surfaces and all four of their edges. Here, after 10 days, composites absorbed the most water at a rate of 4.145%. In test series two (Figure 40), the two surfaces were submerged in water for six days, while the other four sides were appropriately waterproofed. The greatest water absorption rate was reported at 3.883%. This indicates the time to stabilize and the amount of water absorption were both decreased when the waterproofing materials were applied.

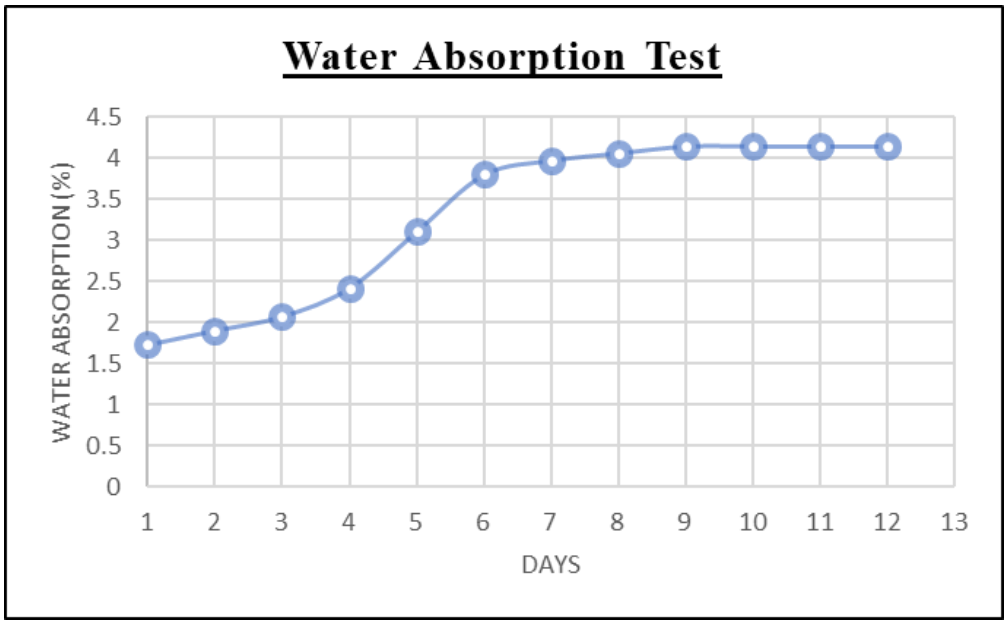


Figure 36: Water absorption for first test series (All 4 edges and two surfaces of samples exposed to water)

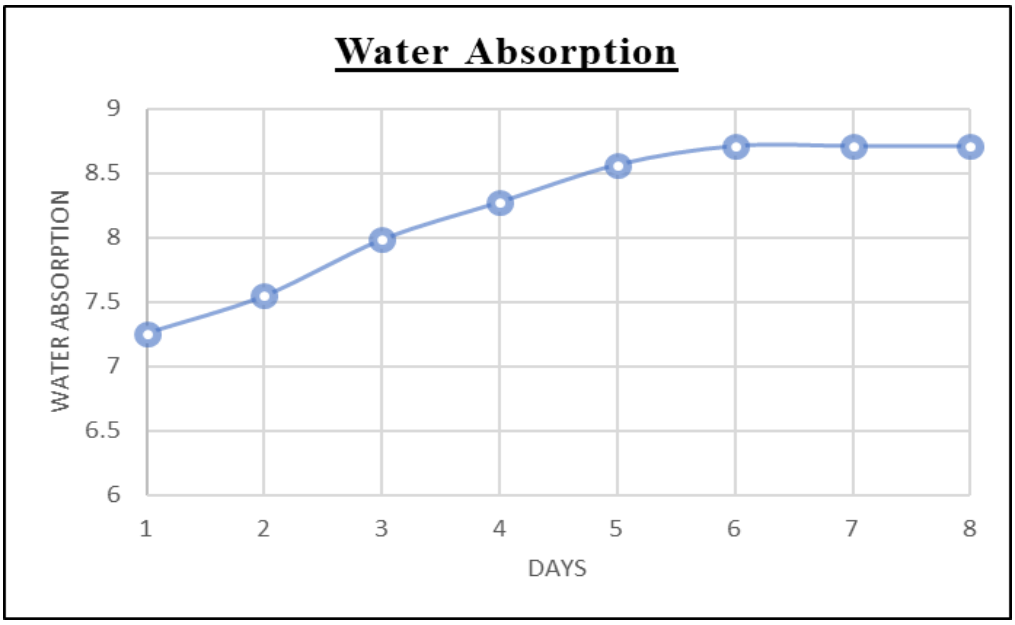


Figure 37: Water absorption for second test series (Two surfaces exposed to water and the other 4 sides are properly sealed with waterproofing material)

According to the results of these two experiments, water absorption was faster in the beginning and decreased as immersion time increased. The ability to absorb water and swell is strongly correlated with density, void content, and the connection between the fiber and matrix [140]. This component increases composite weight because it causes water to become trapped in the void.

Jumaidin et al. [141] and Ramirez et al. [142], claim that natural fiber materials' lower water absorption rates can be attributed to factors like the interfaces' adhesion between the fibers and the matrix, the polymer matrix's higher water affinity compared to natural fibers, the prevention of water absorption by fiber-produced matrices, and the reduction of void content in composites.

4.1.18 Thickness Swelling Test

To examine the alterations in dimensional stability, a test was conducted on the developed composites to measure the swelling thickness. Figure 41 displays the swelling thickness of the composites. The results obtained from the study on kithul fiber-reinforced polymer composites indicate that water absorption and thickness swelling behavior follow a similar pattern. After one week of immersion in distilled water, the thickness swelling of the composites increased. However, as the immersion period extended to nine days, the swelling thickness reached a relatively steady state and became more visible.

The maximum swelling thickness value observed after nine days of immersion was determined to be 8.57%. This suggests that the initial stages of immersion exhibit rapid swelling of the composite's thickness, but the rate of swelling decreases as the immersion period increases.

This behavior is consistent with the moisture absorption characteristics commonly observed in natural fiber composites. Initially, when the composites are exposed to water, the fibers readily absorb moisture, leading to an increase in the thickness of the material. However, over time, the composite reaches a saturation point where the rate of moisture absorption slows down, resulting in a relatively steady state of thickness swelling.

The following calculation was used to calculate the percentage of water absorption.

$$\text{Thickness Swelling } (\%) = \frac{T1-T0}{T1} \text{ x } 100$$

T0 – The specimen thickness prior to soaking

T1- The specimen thickness following soaking

Thickness Swelling after 6 days = $(\boldsymbol{T1}-\boldsymbol{T0})/\boldsymbol{T1}$ x 100% = $(\boldsymbol{3.5\ mm}-\boldsymbol{3.2mm})/(3.\boldsymbol{5\ mm})$ x 100% = 8.57 %.

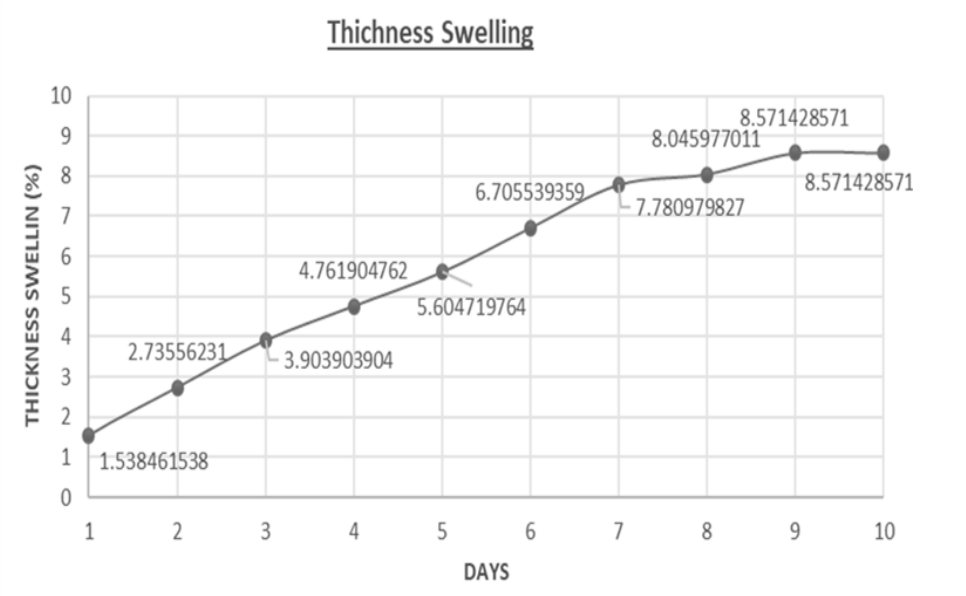


Figure 38: Thickness swelling

These findings corroborated the findings of Edihirej et al. [143] and Sahari et al. [144], on the role of natural fiber in water absorption and thickness swelling behavior. Additionally, thickness swelling and dimensional stability composite are impacted by the ineffective interaction between fiber/matrix and fiber distribution [145].

4.1.19 Flammability Test

Typically, polymers disintegrate at temperatures between 300 and 500 °C for the condensed and gas phases, resulting in flammable liquids, fumes, char, and smoke as well as drips that could be dangerous [146]. The substantial release of heat and smoke can exacerbate the fire's propagation and reduce visibility, leading to significant property damage and posing significant hazards to individuals. In addition, the softening and creep behavior of the polymer matrix and fiber reinforcement under

heating can cause load-bearing composite structures to buckle and fail, which can lead to the destruction of structural integrity [147]. Consequently, the flammability of composites is a critical factor in determining their acceptability by demanding criteria in infrastructure applications.

So, flammability tests were performed on the kithul fiber-reinforced polymer composite following standard procedure. The flammability test results are shown in Table 15. A burning rate of 20.85 mm/min was recorded during horizontal UL-94 tests.

Table 15: Flammability test for developed composite boards

Sample Number	**Rate of Burning mm/min**
1	21.053
2	19.355
3	22.14
Average	20.85

The flammability of fly ash-filled polymer Composite with Jute Fiber reinforcement was determined by Sakthi Balan et al.'s 2022 study. Vertical and horizontal UL-94 testing was carried out following ASTM D3801 and D635 standards, respectively. In tests carried out by UL-94 that were carried out horizontally and vertically, respectively, burning rates of 10.2 mm/min and 11.2 mm/min were noted [148].

All fiber-reinforced composites contain matrix components that are combustible to variable degrees and, when contrasted to metals such as aluminum or steel, can burn vigorously, often with the generation of smoke [149].

CHAPTER 4

4.1 Conclusion

This study aimed to assess the potential and appropriateness of utilizing kithul fiber-reinforced waste thermoplastic composites.

The composites in this investigation were developed by modifying the amount of waste polyethylene added to the fiber content, the temperature and pressure under which the composites were processed, and the length of the kithul fibers. The examinations were conducted to evaluate the materials' tensile strength, flexural strength, impact strength, thickness swelling, water absorption, and flammability. Kithul fiber: Polyethylene with processing temperature and pressure of 150°C and 30 tons as well as 10mm kithul fiber length are used to achieve the highest tensile and flexural strength in lower fiber content.

Kithul fiber composite has a maximum tensile strength of around 12.237 MPa. The maximum flexural strength is 12.51 MPa. The finished product is 20.85mm/min flammable and has an impact resistance of 66.67J/m.

Before the composite process started, seven different natural fibers were characterized to select the best natural fiber to create the composite material. The physical characteristics of seven different kinds of natural fibers (coir, Kithul, Palmyra, banana, bamboo, Watakeiya, and Sisal) were investigated in this study. The observed average diameter of Kithul, Palmyra, Sisal, and Watakeiya ranged from 400μm-525μm. Bamboo and banana fibers have smaller average diameters (201.9625 μm, 156.996 μm) than other fibers. Kithul, Palmyra, bamboo, and Watakeiya scored below zero in the average density test. The average density of bananas and Sisal was more than 1. The surface characterization of pore size, roughness, interfacial bonding between the matrix and the fiber, and accessible contaminants was achieved using SEM examination. The surface textures can bond differently with the selected matrix during structural applications. Extraction processes, soil variation, and biological effects can considerably impact fiber characteristics. The highest water absorption quality can be identified in Banana fibers.

Kithul and Palmyra fibers represent a lower water absorption quality. When considering the results, it can be identified that the fiber diameter, density, surface morphology, cross-sectional area, and water absorption of the fibers vary according to the fiber type. When applying these to structural applications, the outcome may also differ according to the selected fiber type.

Finally, the composite material generated in this study could be utilized as a building material with further development. At this stage, however, only composite materials' tensile and flexural properties were discussed. Other mechanical characteristics were not included because the scope of this stage was limited to these two qualities. Considering the observed results, the final application of this product cannot yet be defined. Further studies are suggested to finalize the application of this product.

Since all raw materials are waste material, the material cost at the factory is zero; only the cost of transportation, steel molds, labor, and electricity costs is considered in cost calculations. The total cost for a one m^2 board is approximately 150 LKR.

Recommended Future Studies

Following the completion of this investigation, other studies will be carried out.

- To figure out the effect of natural fiber tensile strength on composite strength, similar tests involving various fiber tensile strength values are required.
- Similar investigations must be conducted with other matrix types to ascertain how the matrix type affects the composite's strength.
- To find out how fiber orientation affects the composites' strength, a comparable investigation must be conducted using various fiber orientations.
- To determine how to change fiber characteristics, kithul fiber requires a different extraction procedure.
- For produced composites, tests must be performed to determine the fiber/matrix interfacial bond strength while also varying the fiber type and the matrix type to assess the impact of the lowest flexural strength.
- To choose the best composites for the civil sector, a cost-benefit analysis also needs to be performed.

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