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Utilization of regenerated cellulose fiber (banana fiber) in various textile applications and reinforced polymer composites

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Abstract

Fibers are derived from natural resources and are an important commodity utilized by the textile industry. When current supply and future demand are considered, repurposing agricultural waste into fibers is an eco-friendly, appealing choice that may help to reduce environmental pollution and make the textile industry more sustainable. We explained in this review numerous possible secondary sources for Fiber production, with a case study involving banana plant residual biomass, a major agricultural waste in many developing nations. Banana pseudo-stem Fibers, which have exceptional physical and mechanical qualities, are increasingly recognized as essential textile materials. Because of its high cellulose content, good to moderate strength, fineness, Fiber length-to-breath ratio, and other properties. Banana Fibers are used in a variety of industries, including textiles, composites, and automobiles. Furthermore, banana Fibers may be used to make apparel such as dresses, shirts, and rugs, as well as bags, handbags, wallets, purses, belts, shoes, and so on. Banana Fiber may also be used as a reinforced-polymer composite, which is rapidly being used in a wide range of applications because it offers an environmentally friendly and cost-effective alternative to conventional petroleum-derived materials as well as has enhanced physical properties.

Keywords: regenerated cellulose, banana fiber,reinforced polymer composites

Introduction

Green Chemistry is described as the "design of chemical products and processes to limit or eliminate the usage and production of hazardous compounds." This overview and the concept of Green Chemistry were developed approximately 33 years ago, at the start of the 1990s. These had a huge impact on sustainable design. Green Chemistry's goal of reducing risks at all stages of the life cycle has been proven to be economically beneficial.[1]

The majority of organic compounds used today are generated from non-renewable petroleum and natural gas, however, some are still manufactured from coal. After usage, the vast majority of them end up as carbon dioxide, the primary greenhouse gas responsible for global warming.[2] To protect our environment, we must use some preventative measures and technologies that can preserve the natural balance of our ecosystem while also making the end product free of adverse impacts and these products must be based on renewable resources from fields and forests.[3-5]

With a growing population and an increase in food/fuel issues, agricultural sectors that were projected to create more biomass are under a lot of pressure. So it was necessary to utilize plant biomass resources for the production of energy and materials is indispensable for a sustainable society.[6]

More agricultural product supply and demand has led to increased disposal of biomass leftovers and other applications of biomass in many fields such as absorbents, fillers, different clay synthesis, and so on have been well established.[7, 8]

Although no international standard exists to define eco-friendliness, a fiber made from renewable raw materials, using an environmentally friendly and commercially viable process, and having created biodegradability or recycling capability can be considered eco-friendly as shown

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in **Figure 1** which demonstrates the concept of an eco-friendly fiber.[9]

As a result, many programs and activities are being carried out across the world to encourage the use of natural fibers, also known as recyclable, ecologically friendly fibers.[10] Fibers are long, continuous short or long filament polymers classified as follows: Cellulose (for example, cotton and plant-based biomass),[11] protein (for example, animal wool or silks), mineral (for example, asbestos), and synthetic or man-made (for example, polyesters, fossil-derived nylon) Fibers.[7]

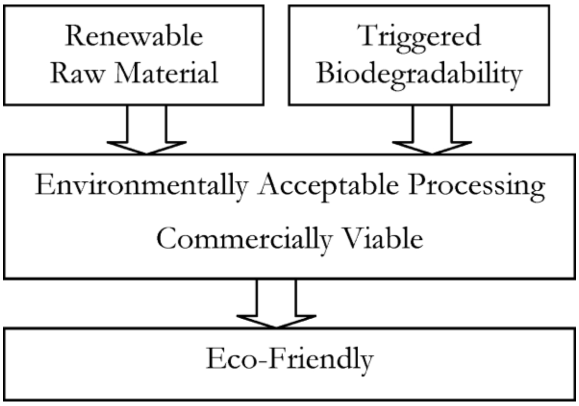

Figure 1 Concept of an eco-friendly Fiber.

Eco-friendly clothing can be termed as clothing made of natural fibers such as organic cotton, hemp, or other waste from plants, clothing that has been organically dyed with vegetables, or any fabrics that use small amounts of water, energy, and chemicals that affect the environment.[3] Sustainable textiles are fabrics that are grown and created in an environmentally friendly way, using minimal chemicals. The best definition of sustainability, according to the United Nations Commission on Environment and Development, is "meeting the needs of the present without affecting future generations' ability to meet their own needs and desires."[4, 10]

Sustainable Fibers offer a solution for businesses dealing with environmental challenges; these Fibers are also advantageous in meeting market expectations for high-quality products these days.[4]

Some factors are constituting sustainable textiles:- The four key aspects are raw material extraction, textile manufacture, additional chemicals, and end-of-life.[12]

1)- Raw material extraction, for example, addresses the land and water necessary to cultivate natural Fibers like cotton and wool, as well as the effects of extracting fossil fuels for synthetic Fibers like polyester or nylon.

2)- Production issues include water and energy.

3)- Additional chemistries, such as dyes, finishes, and coatings, may have an impact on the health of textile workers as well as end product consumers.

4)- Finally, end-of-life considerations include textile biodegradability and the recycling facilities necessary to convert it into fresh raw material.[12]

In this paper, we presented the perspective of recycling plant biomass to generate fibers, along with a case study to promote circular economy principles.

Sustainable Fibers

Fibers derived from plants have received considerable attention in recent years as an alternative to reinforcements derived from synthetic fibers. Because of their lower cost, great flexibility, reduced density, environmental friendliness, and improved stiffness, plant fibers are easier to manufacture than manmade fibers such as carbon and glass.[13]

Poly Lactic Acid (PLA) Fiber

PLA is a linear aliphatic thermoplastic polyester made from 100% renewable sources such as corn, sugarcane, and sugar beet, and the polymer is biodegradable.[14-16] It is created either by ring-opening polymerization of lactide or by polycondensation of lactic acid monomers derived from corn fermentation.[17, 18]

The prospect of decreasing Earth's carbon dioxide level over its lifespan is the reason for its widespread use in the textile business as the degradation of polylactide products is nontoxic and enhances practical applications in biomedicine.[15, 16]

PLA fibers are a completely new type of synthetic fibers made from yearly renewable crops that are melt-spinnable. PLA fiber shares several qualities with typical thermoplastic fibers, such as controlled crimp, smooth surface, and minimal moisture regain. Its mechanical properties are thought to be equivalent to those of traditional polyester (PET) fiber, owing to lower melting and softening temperatures (in comparison to metal and glass), changeable barrier qualities to fit end-use applications, high printability, ease of conversion into other shapes, high stiffness, clarity, gloss, and UV stability. As a result, it has been employed in packaging materials and other items.[18-20]

Soybean Protein Fiber

Soybean Protein Fiber (SPF) is the only protein fiber obtained from natural and renewable sources.[21] Soybean fiber is a regenerated protein fiber manufactured from soybean protein and polyvinyl alcohol (PVA). Soybean fibers are cream in color and have a diameter of around 20 µm.[22, 23]

SPF is the most common plant protein fiber in the natural world, and it is a recently developed skin protectant.[24] This fiber can be mass-produced in large numbers at an acceptable price. SPF has various appealing characteristics that may match the demands of comfortable, elegant, and easy-care apparel.[19, 25] Another benefit of soybean protein is its greater protein content (40% vs. peanuts, 25% vs. corn 10%), as well as its environmentally friendly manufacturing. Furthermore, the ability to modify a plant protein using molecular genetic methods provides the chance to increase the characteristics of the fiber in specific applications.[22]

Casein Fiber

Casein fiber technology offers an alternate method of gaining some of the benefits of milk without drinking it, but rather by wearing it in the form of clothes. Casein fiber is made from skimmed cow's milk, after removing all the water content, milk is skimmed. A new bio-engineered approach is then used to create a protein-spinning liquid. This liquid is suitable for the wet spinning process, which produces the final high-quality material fiber. A dissolvable is used by many companies when spinning, and smaller size zinc particles are implanted in the fiber, giving it bacteriostatic and robust properties.[26, 27]

The major component of this fiber is casein proteins, which consist of 15 different types of amino acids. These amino acids help skin nutrition. Milk protein fiber is a product of nature, science, and technology, and as such, it combines the benefits of natural and manufactured fibers.[28, 29] The fiber has a glossy look that resembles Mulberry silk. Casein fibers can carry out biological healthcare functions and have natural and long-lasting antimicrobial properties. Fabrics created from these fibers have great water absorption and air permeability, making them extremely comfortable.[29, 30] They have a pH similar to human skin.[28] Other essential characteristics of these fibers are biodegradability and renewability. The fiber is white and shiny, with a smooth surface and subtle striations, and its cross-section varies from bean to virtually spherical.[19]

Bamboo Fiber

Bamboo fiber is made from cellulose extracted from bamboo tree pulp. Bamboo is derived from natural resources that degrade fully in soil via the action of microorganisms and sunlight without harming the environment.[31] Fiber is formed using alkaline hydrolysis and multi-phase bleaching of bamboo stems and leaves, followed by chemical processing of the starchy pulp formed during the process.[32]

Bamboo fiber has a high level of permeability and cooling due to the existence of many microlevel gaps and holes in its cross-section that make it softer than cotton and encourage moisture absorption.[19]

The fiber has antifungal, antibacterial, and UV light resistance properties. It is also extremely robust, stable, and strong, with a high tensile strength. Bamboo fibers are mostly employed in the textile sector for creating clothing, towels, and bathrobes due to their diverse characteristics.[31] Because of its antibacterial properties, it is used to make bandages, masks, nursing wear, bacteriostatic curtains, and a variety of other items. [32-39]

Pineapple Fiber

Pineapple leaf fiber (PALF) is extracted from the plant's leaves, which are around 1-1.5 m tall and have dark green, sword-shaped leaves with spines. Among leaf fibers, PALF has the highest tensile strength. On the other hand, it has the lowest elongation at the break of any leaf fiber (1.6%).[40, 41]

Pineapple fiber is white in color, soft and smooth, and has a silky feel to it. The availability of low-cost lignocellulosic natural fibers in tropical nations, such as pineapple leaf fiber (PALF) presents a unique opportunity to investigate the possibility of using them to synthesize low-cost biodegradable materials for a variety of applications.

The following are the key benefits of employing these fibers as reinforcements in polymer composites: (1) low density, (2) cheap cost, (3) nonabrasive nature, (4) low energy consumption, (5) high specific characteristics, and (6) biodegradability.[42, 43]

Okra Fibers

Okra plants are easy to grow since they are drought-hardy and use little water. Okra has been eaten for ages. However, research has been ongoing on using stem waste as a natural source for fiber production.[44] The fibers of okra stems are composed of 67.5% cellulose, 15.4% hemicellulose, 7.1% lignin, 3.4% pectin, 3.9% oil wax, and 2.7% water-soluble compounds. Okra also includes bast fibers, which account for 10-25% of the plant's weight.[45] Water retting was used by the majority of the researchers to separate fibers from okra stems because it produces more consistent and high-quality fibers. The recovered fibers are then thoroughly dried and kept away from water and sunlight.[46]

The lignin level of okra fiber is low, which promotes yellowing and photochemical breakdown. It also has a large molecular weight. As a result, the okra fibers have high color fastness and mechanical characteristics but moderate elongation at break. Okra fibers and other traditional stem fibers have similar properties, and okra fiber has a brilliant and strong structure.[26]

Coconut Fiber

Coconut fiber is extracted from the husk of the coconut plant, which is a member of the palm family.[47] The fruit weighs around 1-2 kilograms and has roughly 30% husk. The traditional process of fiber extraction is ‘retting' (dipping coconut husk in a backwater lagoon for 6-12 months) to create whiter, softer, and spinnable retted fibers.[48]

Individual fiber cells are small and spherical with thick cellulose walls. Coconut fibers range in length from 15 to 35 cm. Coconut fiber contains cellulose, hemicellulose, and lignin as major compositions.[49, 50] The fibers are light in color and either gold-yellow or brown. The plant is grown in Europe, Africa, Asia, North America, and Australia. Coconut fiber is used in the manufacture of ropes, mats, brooms, brushes, paintbrushes, mattress filling, and upholstery for furnishings.[19, 47, 51, 52]

Corn Fiber

Corn fiber is a common and cost-effective byproduct of the corn wet milling process, accounting for around 10% of the processed dry corn.[53]

Corn is an agricultural crop that contains a high concentration of starch, which growers take from plant fibers and convert into sugars, which are then fermented and divided into polymers.[54] The corn fibers are paste-like at this phase in the process and are subsequently extruded into fine strands that are cut, carded, combed, and spun into yarn. Apart from the chemical operations, the other part of the procedure is comparable to that of wool. Corn fiber is a man-made fiber composed completely of renewable materials.[55] These fibers contain the performance benefits commonly associated with synthetic materials, as well as qualities that complement natural items such as cotton and wool. Maize fiber is made up of lactic acid, which is made by turning maize starch into sugar and then fermenting it to form lactic acid. Corn fiber producers say that their fibers may be used for sportswear, jackets, outer coats, and garments, among other things.[12, 56-60]

Sugarcane Fiber

Sugar cane is a potentially rich source of natural fibers that has yet to be fully realized.[61] To separate the fibers from various sites in the plant, a simple physical process was established, yielding nine components.[62] It contains 45% fiber, composed of 45% cellulose, 33% hemicelluloses, and 20% lignin. Long and fine fibers are found in the stalk's rind, whereas short fibers are found in the stalk's interior, known as the pith. Bagasse is a cane stalk combination that includes the exterior rind mixed with the interior pith. The lengths of the fibers are irregular and unregulated. Bagasse, on the other hand, may be utilized to make sustainable textiles because of its high fiber content, notably its cellulose rate.[61, 63]

Oil palm Fiber

Oil palm fiber (OPF) is a secondary product collected from empty fruit bunches that were used as reinforcement in biocomposites; fibers may also be taken from other portions of the tree, but the yield is relatively low when compared to fruit bunches.[64, 65] Empty fruit bunches cause trash disposal issues, however fibers may be recovered from them. To remove the fibers, the retting procedure is utilized, with water retting being the most prevalent. These fibers are strong and hard, with qualities like coconut fibers. The OPF is composed of approximately 65% cellulose and 29% hemicellulose.[40]

Banana Fiber

Banana (Musa acuminata) is a fruit that is always and easily available, regardless of the season. When collecting banana fruits, the plant that was used for harvesting cannot be reused. This results in a tremendous amount of biomass being produced.[66] This biomass especially pseudo stem and peduncle are potential sources of natural fiber, which could help the industry by lowering purchasing materials costs. Furthermore, as compared to other natural fibers, banana fiber extraction would be more environmentally friendly.[13, 67] Due to a lack of sufficient sustainable technology for economic application, the fibers end up as trash. Banana fiber may be used as a raw material in a variety of goods such as paper, cardboard, tea bags, and currency notes, as well as strengthened as a polymer composite in stylish garment material.[37, 52, 68-79]

Banana fiber is a cellulosic bast fiber with exceptional mechanical characteristics. Banana fiber possesses high explicit strength qualities that are comparable to those of conventional materials, such as glass fiber.[80, 81] Among many natural fibers, banana fibers contributed to the development of several qualities such as swelling, mechanical, dielectric, and thermal deterioration.[13] **Fig 2** illustrates the banana plant.[81]

Figure 2 Banana plant

Banana, a natural lingo-cellulosic plant fiber, is harvested from the banana plant's leaf or pseudo stem, which grows abundantly in tropical locations. The fiber has a cellulose content of 71.08%, a hemicellulose content of 12.61%, and a lignin content of 7.67%.[82] Cellulose is the major source of excellent performance in plant fibers, because of its crystalline nature and ß-4 linked D-glucan chained structure. Crystalline cellulose has a Young's modulus close to Kevlar and is possibly stronger than steel. Hemicellulose has an amorphous structure, because of its short and branched chains containing pendant side groups. Lignin is a 3D copolymer that is primarily responsible for plant fiber cell stiffness.[83]

The stem is made up of 15-25 sheaths of leaves that are covered by a central core. As the plant gets older, the sheaths transform into banana leaves for later use. A typical plant may reach a height of 7.5 meters surrounded by 8-12 large leaves and a maximum leaf width of 30 cm, after which it begins to be useful, indicating that it has produced numerous fruits and flowers throughout its life.[82] The component of the plant pseudo stem is illustrated in **Fig 3**.[84]

Banana fibers feature remarkable strength, lightweight, shorter length, fire resistance, firm dampness ingestion quality, extraordinary potential, biodegradability,[80, 85] low cost, lower CO_2 absorption, safer production procedures, and high electrical resistance.[82]

Banana fiber extraction

The banana fiber extraction method was carried out using leaf sheaths cut from the plant's pseudo-stem. When a pseudo-stem is put into a peeling machine, several layer bundles are separated from the exterior, middle, and interior sections.[82, 86] The machine is made out of a long shaft with a rotating drum installed on top. The shaft is linked to a chain drive that is driven by an electric motor. The drum shaft is attached to many rotating blades. The banana plant pseudo-stem was put into a machine that beats, smashes, and takes the fiber out of the stem. The removed fibers are delivered by a belt connected to the machine's side.[87] The outside and middle portions of the pseudo-stem extract more fiber, whereas the interior portion of the pseudo-stem extracts less fiber. The explanation was due to low strength and stiffness, which makes fiber peeling difficult. The machine not only creates fibers but also non-fibrous compounds known as gums.[83, 88-90] The extracted fibers were observed to be in long strands and slightly dull yellowish in color.[68] **Fig 4** shows the extraction process done for the production of banana fibers from the banana plant's pseudo-stem.[13]

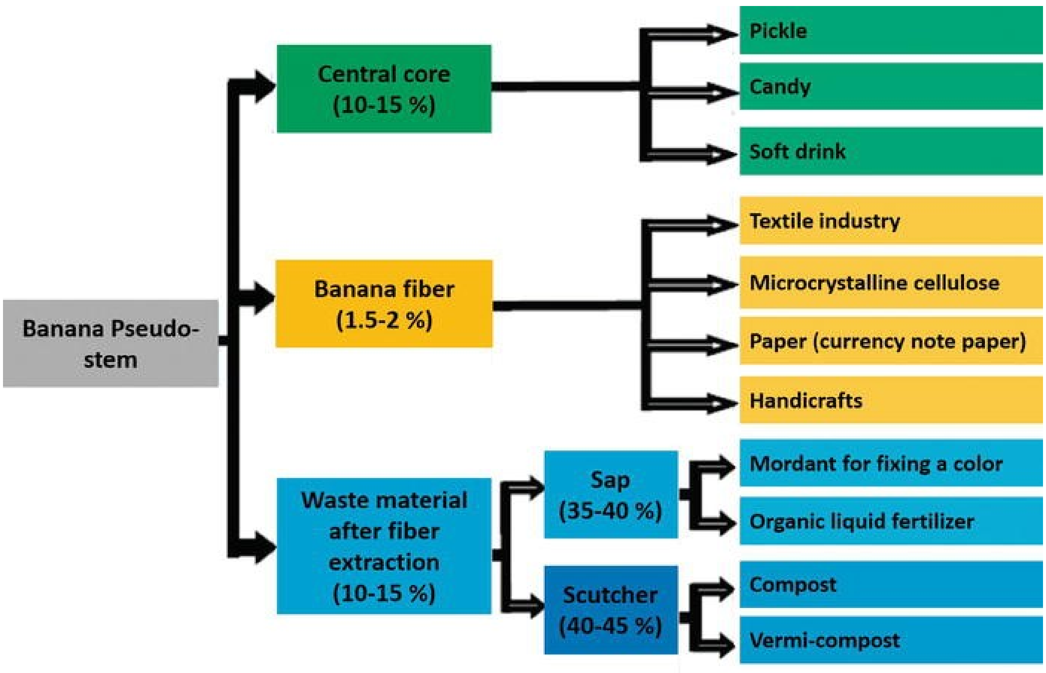

Figure 3 Banana Pseudo-Stem Fiber components

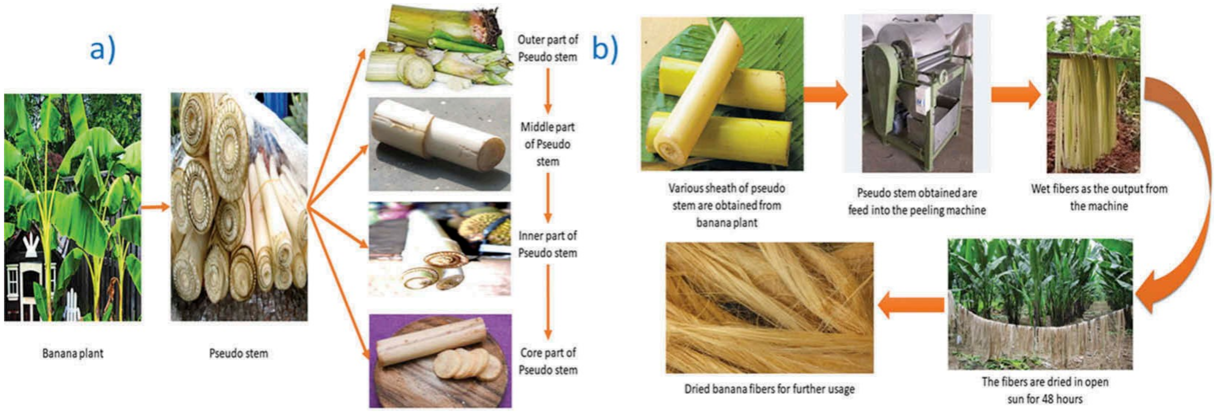

Figure 4 Composite preparation: a. Pseudo-stem extraction from banana plant; b. Preparation of banana Fibers.

Pre-treatments of extracted fiber (Degumming procedure)

After extracting the fiber from banana stems, banana fiber samples were treated with chemicals and enzymes to analyze their physical properties and to remove the gums that formed alongside the fibers during the degumming process.

Banana fiber was cut into 25 cm lengths for physio-biological, physio-chemical, physio-enzyme and chemical combination treatments.[68]

Physio-biological treatment

Mechanically extracted fibers were treated with 5% enzyme concentrations (pectinase, xylanase Hemicellulase, and cellulase) in acid medium 2.5 and 3.5 at 55 °C, because they are capable of breaking down complicated plant tissue molecules into simpler ones, such as galacturonic acid.[67] And also softens the fiber by removing pectin, waxes, lignin, and hemicellulose. The enzymes cellulase and pectinase removed additional impurities from the banana fiber, softening it. There were no positive outcomes for improving the whiteness index. However, when the fiber was individually treated with enzymes, just one specific contaminant was eliminated. Because enzymes are particular in their function, the contaminants were not eliminated equally. Hemicellulase enzyme removes hemicellulose from fiber, pectinase enzyme removes pectin, and cellulase enzyme influences cellulose and softens the surface. As a result, the fiber was treated with a mixture of enzymes. It was also discovered that the weight loss in fiber increased with concentration and time. The more the weight loss in the fiber, the greater the strength loss, since the elimination of additional contaminants and fats would decrease the binding force and therefore decrease its resistance to breaking under load. [91]

After that, the treated banana fiber samples were thoroughly washed with running water and dried in the oven. The dried banana fibers are then collected and stored for future use.[68, 84]

Physio-chemical treatment

Mechanically extracted fibers were first scoured in a solution comprising 10 grams per liter of natural banana tree trunk ashes and caustic soda (NaOH) detergent at 75°C for 30 minutes in a fiber beaker. Liquor ratio 1:50, followed by air drying of fiber.[92, 93] Second the fiber was treated for 2 hours at 95 °C with 6% bleaching agents (hydrogen peroxide), 2% sodium silicate, 3% caustic soda, and 0.2% wetting agent. The liquor ratio in the treatment process is 1:50. Then samples were neutralized using dilute acetic acid.[92] After that, the treated banana fiber samples were thoroughly washed with running water and dried in the oven. The dried banana fibers are then collected and stored for future use.[68]

Physio-enzyme and chemical combined treatment

Mechanically extracted fibers were treated with 5% pectinase enzyme concentrations at 45-55 °C. For the enzyme treatment, the pH was kept between 2.5 and 3.5. The liquor ratio was 1:50. The treated banana fiber samples were thoroughly washed with running water and oven-dried. The enzyme-treated samples were then treated for 2 hours at 95 °C with doses of 6% hydrogen peroxide, 2% sodium silicate, 3% caustic soda, and 0.2% wetting agent. The treatment employed a liquor-to-water ratio of 1:50. These combination-treated banana fiber samples were then completely cleaned and dried in the oven. The dried banana fibers are then collected and stored for future use. We can conclude the stages of banana fiber production and application in **Fig 5**.[94]

Types of banana fiber

The quality of the fiber inside the stem varies I. Inner fibers (fine, smooth, luster, and natural shine) - smoothest fabrics such as kimonos and saris.

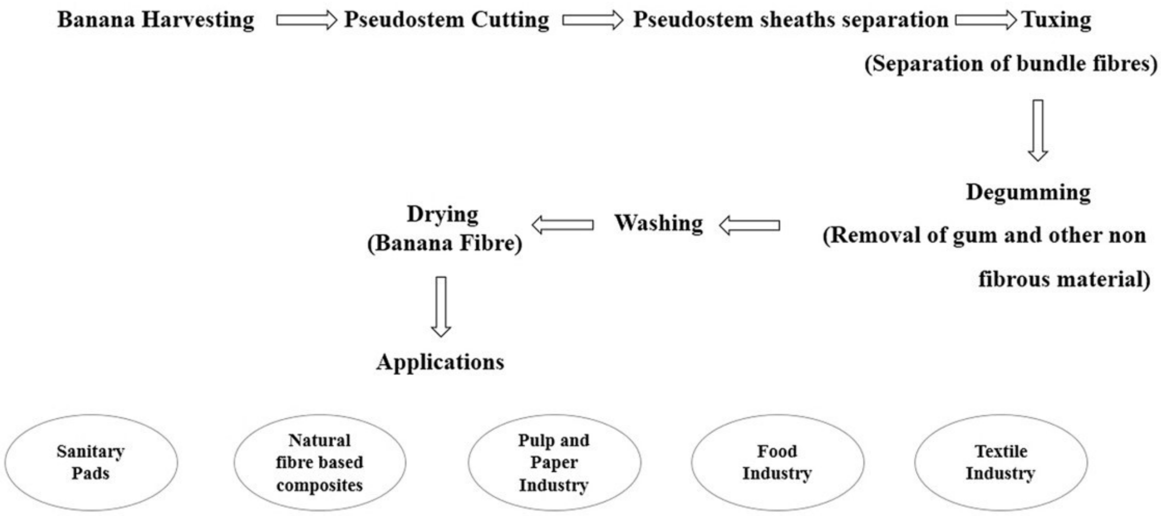

Figure 5 Extraction and application of banana Fiber

II. Outer strands (rough)-weaving baskets and creating handbags and these types are presented in **Fig 6**.[81]

Banana fiber spinning

To make naturally rough banana fibers appropriate for spinning operations, various softening methods have been used. The collected and dried fiber is then spun. These fibers are divided into 3 cm lengths and may be spun into yarn using an open-ended spinning method.[95] **Fig 7** illustrates banana yarn and knitted material.[96]

Banana yarn weaving

Yarns are threaded onto looms to begin the weaving process. Banana fabric may be manufactured from a variety of fabrics. The thickness and texture of the banana fabric are determined by the section of the banana stem utilized for extraction. The fibers obtained from the outside layer of the stem are rough, but the fibers removed from the inner surface are fine, lustrous, and smooth.[95]

(A) Coarse(rough) Fiber (B) Fine and smooth fiber (C) banana fiber fabric silk looks like

Figure 6 Types of Banana Fiber

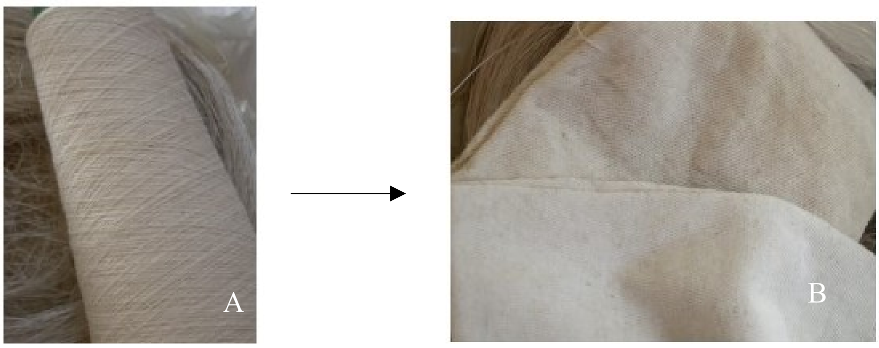

Figure 7 (A) Banana spun yarn (B) Banana fiber knitted trial

Characteristics of Banana Fiber

Banana pseudo-stem fibers are naturally occurring leaf fibers. It has unique physical and chemical qualities, as well as numerous additional features that make it a high-quality fiber. The properties of the banana tree make it one of the most valuable raw materials not only for the textile and fashion sectors but also for related industries.[97]

Physical and mechanical properties

In terms of physical qualities, the banana pseudo-stem fiber has been reported in the literature to have a good modulus of elasticity, tensile strength, and stiffness, making it a potential fiber material as illustrated in **Table 1**.[96] Because of its high alpha cellulose and low lignin concentration.[10] It is biodegradable and has no negative environmental impact, making it an eco-friendly fiber.

Accordingly, it was monitored that the banana fiber is lighter than the flax fiber. While the physical appearance of banana pseudo-stem fiber is similar to that of ramie and bamboo fiber, its spin ability and fineness are significantly greater. It has an average fineness of 2400 Nm. It is a hard fiber with a low strain at break. It has a glossy look due to the extraction and spinning procedures. It has a low density and a high moisture absorption rate. It absorbs and releases moisture very quickly. fiber from banana pseudo-stem exhibits a high degree of crystallinity with a spiral angle of roughly 15°. The molecules are packed closer together in the crystalline area. The amorphous area in the acid and alkali-treated banana pseudo-stem fibers was higher than in the untreated fiber.[84]

Table 1 Physical and mechanical properties of banana fiber.

Fiber properties	
Tenacity	29.98 g/denier
Fineness	17.15 Denier
Moisture Regain	13.00 %
Elongation	6.54
Alco-ben Extractives	1.70 %
Total Cellulose	81.80 %
Alpha Cellulose	61.50 %
Residual Gum	41.90 %
Lignin	15.00%

Chemical properties

Banana fiber is mostly composed of cellulose, hemicelluloses, lignin and other components as observed in **Table 2**.

Banana fiber is resistant to weak alkalis, phenol, formic acid, chloroform, acetone, and petroleum ether. It dissolves in concentrated hot sulphuric acid. Banana fiber has less lignin than jute fiber.[98]

Table 2 Chemical properties of banana fiber

Constituents: -	%
Cellulose:	67.4
Lignin:	4.8
Ash:	1.0
Moisture:	7.5
Cold water Soluble Compounds:	1.9
1% NAOH Soluble Compounds:	28.5

The result of using alkali NaOH at the optimal concentration of 11g/l and the treatment duration of 2.5 hours at 90. Under ideal circumstances, there are noticeable changes in fiber composition because of alkali treatment. Lignin removal from mechanically separated banana fiber is at least 40%. The cellulose content has increased by 20%. The hemicellulose content is similarly lowered by half of its original value. The surface morphology demonstrates an opening in the fiber groups and strong hydrogen bonding has developed on the fiber, providing it with improved mechanical properties.[10] The elimination led to lower density as hemicellulose and lignin components resulted in an increase in density. The moisture regain of the fibers increases, making the fiber more hydrophilic and appropriate for textile applications.[99] This means that banana fibers prefer to dissolve in NaOH, where their weight is enhanced.[100]

In most circumstances, the tensile strength of banana fiber is reduced when it is treated with chemicals, particularly sulfuric acid (70% H_2SO_4), where the fiber is completely dissolved, and the tensile strength is eliminated. For other chemicals, such as Acetone (C_3H_6O), Phenol (C_6H_6O), and Nitrobenzene ($C_6H_5NO_2$), the weight of the fiber remains practically unchanged, indicating that the weight of the fiber is not impacted by the treatment with such chemicals. Fibers are destroyed in Sulfuric Acid (H_2SO_4), so their weight is zero.[100, 101]

But when the fabric was treated with potassium permanganate, and chromium sulfate as a reducing and oxidizing agent, it was discovered that chromium sulfate treatment in a single stage lowers the density of all fibers. While potassium permanganate treatment lowered the tensile strength of all fibers tested.[10] **Table 3** illustrates the Effect of Various Chemicals on banana Fiber. While **Table 4** demonstrates the colour reaction of Fiber.[98]

It was also explored that the natural Fibers derived from the banana plant stems have antibacterial properties. This investigation revealed a significant bacterial inhibit zone in banana cellulose Fiber at various microgram levels.[102]

Table 3 The Effect of Various Chemicals on Banana Fiber

Solvent	Reaction
Dilute NaOH (1%)	No reaction even on heating
Conc. NaOH (20%)	No reaction in cold but on heating and boiling for several minute, the fibre swells.
Dilute HCL	No effect
Conc.HCL	No effect
Dilute HNO3	No reaction
Conc.HNO3	On heating color changes to yellow and fibre disintegrates
Dilute H2SO4	On heating slight swelling and disintegrates of fibre
Conc.H2SO4	Dissolves fibre completely
Phenol	No effect
Formic acid	No effect
Acetic acid	Fibre become soft
Petroleum ether	No effect
Chloroform	No effect
Cuprammonium	No effect
Acetone	No effect

Table 4 The colour reaction of Fiber

Reagent	Color
Zink chloride & iodine reagent	Golden yellow
Para – Nitro aniline reagent	Bright orange
Potassium permanganate	Pink
Meliorate green	Green
Iodine and sulphuric acid reagent	yellow

Microscopic Properties

Various microscopic approaches have been used to investigate the longitudinal and cross-section morphology of banana Fiber. The process of extraction has a considerable impact on the physical shape of the Fiber. The surface of the raw Fiber is slightly rough (**Figure 8a**) and may retain some debris after hand or mechanical separation. Chemical degumming is one of the extraction procedures that yields Fibers with a flat surface (**Figure 8b**). The alkali and enzymes remove the Fiber's pectin, hemicelluloses, and a small amount of lignin, resulting in a smooth surface. The banana Fiber appears dissimilar and non-spherical in cross-section (**Figure 8C**), although the cell wall is thick and the inner lumen is elliptical, thin, and elongated.[68, 103]

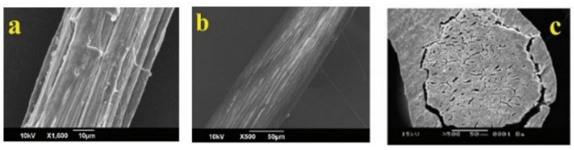

Figure 8 SEM images of banana Fiber (a) raw surface (b) degummed surface (c) Fiber cross-section

The macro, micro, and nano Fibers are shown in the AFM topography (**Figure 9**).

AFM investigation reveals additional Multi fibrillar structure. The average nanofiber diameter was calculated to be around 30 nm. To create micro and nano Fibers, the intermediate lamella and main cell walls are removed more effectively. As a result, the surface is more cellulose-rich, and the Fiber dimension has been effectively reduced to the nano range.[103]

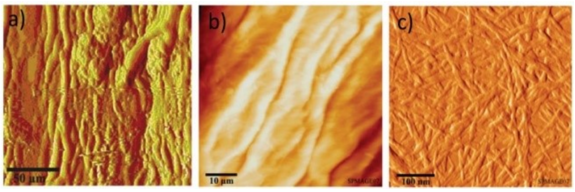

Figure 9 AFM topography of (a) macro, (b) micro, and (c) nano Fibers derived from banana pseudo stem

Dyeing of banana fiber

Dyeing of banana fiber with natural dyes

The fiber dyeing process has been separated into the following steps: I. Preparation of the substrate (to be dyed material); II. Preparation and usage of bio-mordants; III. Preparation and application of natural dyes in the substrate (fiber); IV. Washing. The dyeing steps are illustrated in **Fig 10**.[104, 105]

The dyeing and cold bio-mordant of the fibers yielded the finest results, with a 24-hour rest bath and 12-hour dyeing. Thus, it is aimed to provide new options for natural dyeing using materials and sustainable treatment processes applied to natural fibers.[104-106]

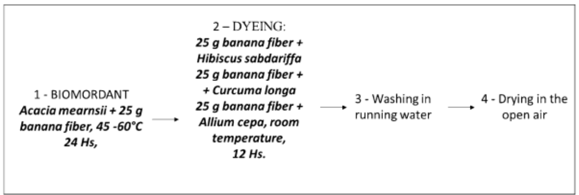

Figure 10 Stages of the bio mordant and dyeing process of banana fibers

Dyeing of banana fiber with synthetic dyes

The samples were scoured and bleached to prepare them for the next operations and this recipe is explained in **table 5**. Then banana fiber was processed and dyed according to the instructions below.[107]

The scoured bleached banana fiber was dyed with Four dyes: reactive, vat dye, direct dye, and basic dye. The fibers were then colored using a sample dyeing machine. For different colors, the pH of the dye bath was modified with soda ash and acetic acid. After that, the samples were pressed and dried. The dyeing recipe is mentioned below in **Table 6**.[107]

Table 5 Recipe of Scouring and Bleaching

Recipe	Amount
Detergent	1gm/L
NaOH	1gm/L
H_2O_2	5gm/L
Soda ash	5gm/L
Wetting agent	1gm/L
Sequestering agent	1gm/L
Time	30 min
Temperature	90 °C
pH	10.5
M:L	1:10

Table 6 Dyeing recipe for different dyes

Types of Dyes →	Direct dyes	Basic dyes	Reactive dyes
Sample weight	5gm	5gm	5gm
Wetting agent	1gm/l	1gm/l	1gm/l
Sequestering agent	1gm/l	1gm/l	1gm/l
Shade %	1.5%	1.5%	1.5%
Glubar Salt	20gm/l	20gm/l	60gm/l
Soda Ash	3 gm/l	-----	15gm/l
Acetic acid	-----	1.5 gm/l	----
Time	40 min	40 min	40min
Temperature	90°C	80 °C	60 °C
pH	7.5	4.5	10.5
M:L	1:20	1:20	1:20

Table 7 Recipe for vat dyeing (vatting)

Recipe	Amount
Sample weight	5gm
Shade%	1.5%
Hydrose	5 gm/l
Soda ash	5 gm/l
NaOH	3 gm/l
Sequestering agent	1 gm/l
Time	15 min
Temperature	70 °C
pH	11
M:L	1:20

Table 8 Recipe for vat dyeing (dyeing)

Recipe	Amount
Salt	15 gm/l
Temperature	70 °C
Time	30 min
M:L	1:20

Table 9 Recipe for vat dyeing (oxidation)

Recipe	Amount
Acetic acid	1.5 gm/l
H_2O_2	2gm/l
Temperature	80 °C
M:L	1:20

The shade and fastness characteristics acquired using synthetic dye demonstrate that synthetic dyes may be used to dye banana fiber. Colorfastness to washing and color fastness to rubbing were both excellent for all dyes employed. However, it has been demonstrated that samples colored with reactive, vat, and basic dyes exceeded direct dyes in terms of wash fastness. Colorfastness to rubbing was excellent for all four samples. According to the description above, vat, reactive, and basic dyes may be effective dyes for dyeing banana fiber for bulk production.[107] The primary issue faced during the dyeing process of banana fiber is the lignin cementing material, which interferes with the absorption property. As a result of the pretreatment method, lignin impurities were eliminated, proving that banana fiber dyeing behaviors are more comparable to cotton dyeing.[108]

Finishing of banana fiber

Water Repellent Finishing

The produced banana samples were treated with a water-repellent chemical (perfluoroalkyl acrylic) by pad-dry-cure procedure at varied concentrations. Excess chemicals were squeezed with a padded roller, then dried in an oven, and cured for a few minutes at a temperature of 160-170 °C. Then water absorbency tests were performed using drop and absorption techniques.[109]

Water repellence (WR) has a major effect on the banana samples since it reduces absorbency greatly. Without WR, a water drop absorbs in 2.38 seconds, but 1% WR extends the period to 1.25 hours. The water drop absorbs in 2.69, 4.2, and 4.67 hours for 5%, 10%, and 20% WR, respectively. It is obvious from **Fig 11** that the contact angles on water droplets increase with WR concentration. In the case of 10% WR, all water droplets are more round than others, with contact angles greater than 90, making all nonwovens extremely water resistant.[109] (

Flame retardant finishing

Fire is a major source of death and injury, as well as property destruction. To prevent fire-related deaths, which are among the most serious types of deaths, the use of flame-retardant materials is critical. The chemical composition of the fiber; ease of burning; fabric weight and structure; flame retardant efficacy; environment; and laundry conditions all influence a textile fiber's flame resistance. Because of their strength and composition, natural fibers would be extremely useful.[110]

The chemical retardant Eco flame CT6 was finished using the pad-dry cure method at a curing temperature of 130-160° C at a curing time of 30 minutes and its flame resistance was tested.

It was demonstrated that the fabric had an effective flame retardant property and was categorized as a class I fabric according to the ASTMD_1230/94 method.[110]

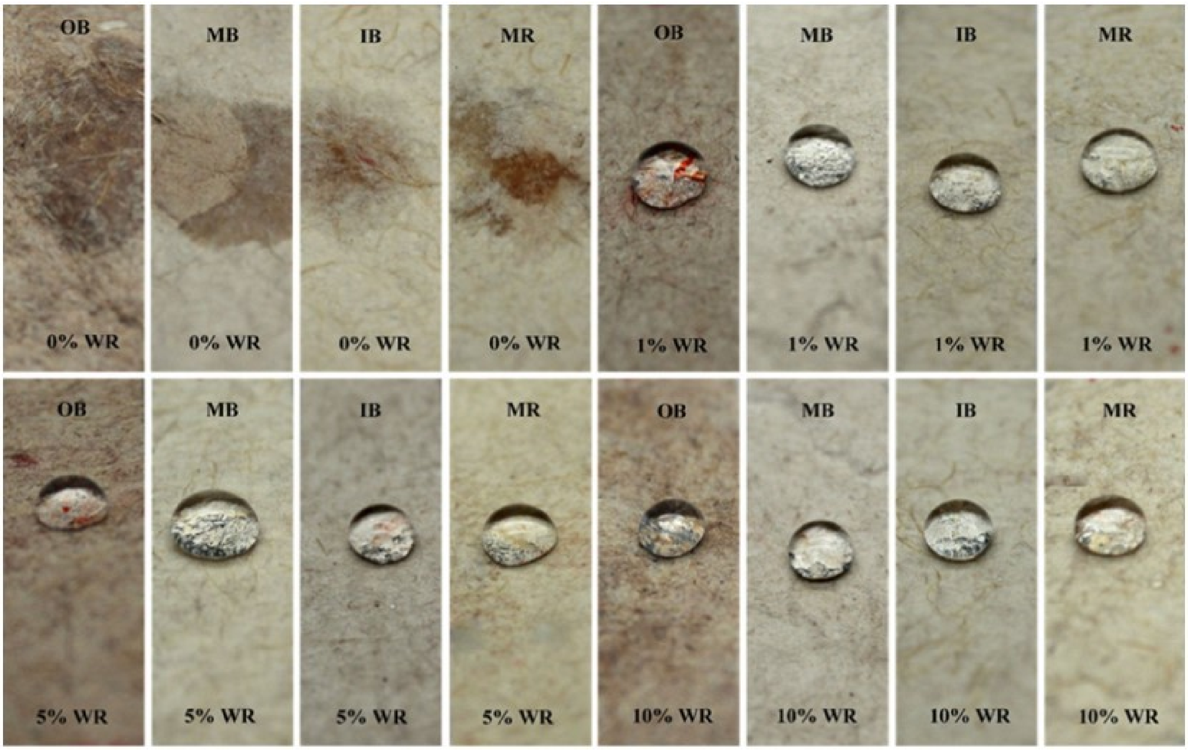

Figure 11 Photographs of water drop after 5 seconds of dropping in different nonwovens at different water-repellent concentrations.
OB) Fiber extracted from outer bark, (MB) Fiber extracSted from middle bark, (IB) Fiber extracted from the inner bark, and (MR) fibre extracted from the midrib.

Application of banana fiber

With so many great features, this fiber is gaining popularity in the fashion industry, with numerous well-known fashion lines and designers using banana-based fabric. In comparison to other synthetic fibers, banana fiber is both environmentally friendly and recyclable. Synthetic fiber production procedures have been proven to be hazardous, nonbiodegradable, and energy-intensive.[111]

Banana Fiber had an extremely limited application in the past and was used to make ropes, matting, and some other composite materials. With increased environmental consciousness and the importance of eco-friendly materials, banana Fiber has been recognized for all of its beneficial properties, and its application is expanding in various industries such as clothes and home furnishings, sleepwear, casual women's wear, bridal clothing, and home decor.[97] However, in Japan, it is utilized to make customary clothing such as kimono and kamishimo.[112] People there still like it as summer outfits since it is lightweight and comfortable to wear. Banana fiber is also used to manufacture high-quality pillow covers, neckties, wallets, tablecloths, and curtains, among other things. Carpets constructed with banana silk yarn fibers are likewise quite popular all over the world. The fiber component of the pseudo stem that was left over after starch extraction was used to make paper pulp. [98, 113] **Fig 12** illustrates some uses of banana fiber.[112]

Figure 12 Application of Banana Fiber

Comparison between cotton, viscose, and banana fiber

Source Material

Cotton: Cotton fibers come from the seed hairs of the cotton plant (Gossypium species).

Viscose: Viscose, also known as rayon, is derived from wood pulp, usually sourced from trees like pine, spruce, or bamboo.

Banana Fiber: Extracted from the pseudo stems of banana plants.[114]

Production Process

Cotton: Is primarily grown in warm climates and requires well-drained soil. It undergoes a series of growth stages, starting from planting seeds, germination, flowering, and ultimately boll development where the cotton fibers are enclosed, and the fibers are separated from the seeds through a process called ginning. After ginning, the cotton fibers undergo further processing, including cleaning, carding, and spinning, to produce yarn or thread that is then woven or knitted into fabric.[115]

Viscose: It is Produced through a chemical process involving the extraction of cellulose from wood pulp, then the extracted cellulose undergoes a chemical process, where it is treated with caustic soda and carbon disulfide, to convert cellulose into a soluble compound. This liquid is then forced through spinnerets, creating filaments. These filaments are then solidified through a regeneration process, often involving the use of chemicals like sulfuric acid. The resulting material is then washed, dried, and cut into fibers suitable for various applications.[116]

Banana Fibers: Are extracted from banana pseudo stems, which undergo a process called decortication, where the outer layers are scraped away to reveal the fibers. The fibers are then combed to remove impurities and spun into yarn or thread suitable for weaving or knitting.[103]

Environmental Impact:

Conventional cotton cultivation can be resource-intensive, requiring significant water and pesticide use.

The viscose production process involves chemicals, and the environmental impact depends on the source of wood pulp and the manufacturing practices.

Banana Fiber is generally considered more sustainable as it often involves less chemical use, and the raw material comes from the byproducts of banana cultivation.[73]

Properties:

Cotton: Soft, breathable, absorbent, and comfortable to wear.

Viscose: Smooth, drapes well, and has a silk-like appearance. It can be lightweight or heavy depending on the production process.

Banana Fiber: Strong, durable, and has a natural sheen. It can be coarse or fine, depending on the extraction process.[117]

Applications

Cotton: Widely used in clothing, home textiles, and various industrial applications.

Viscose: Used in clothing, linens, and as a substitute for silk in various applications.

Banana Fiber: Traditionally used for making textiles like mats and ropes and emerging as a sustainable alternative in fashion and home goods.

Cost

Cotton: Pricing can vary based on factors such as quality, type, and production methods.

Viscose: Generally, less expensive than natural fibers like silk, but prices can vary.

Banana Fiber: May be more expensive due to the labor-intensive extraction process and limited availability compared to cotton and viscose.[118]

Effect of acid, alkali, and oxidizing agents:

Cotton fibers

Acid: Cotton is resistant to moderate acids in general. Strong acids, on the other hand, can damage the cellulose structure in cotton fibers, causing weakening and loss of strength.

Alkali: Cotton has a high resistance to alkalis. While strong alkalis can damage cellulose, cotton fibers are more stable in alkaline than acidic environments.

Oxidizing agent: Cotton can be damaged by powerful oxidizing chemicals, resulting in fiber breakdown and color loss.[119]

Viscose (Rayon)

Acid: Viscose is susceptible to deterioration under acidic environments. Strong acids can degrade the cellulose structure, causing the fiber to lose strength.

Alkali: Viscose is susceptible to alkali degradation. Strong alkalis can degrade cellulose chains, resulting in a decrease in fiber strength.

Oxidizing Agent: Viscose is susceptible to oxidizing chemicals, which can cause yellowing and fiber deterioration.[117]

Banana Fiber

Acid: Banana fibers are often acid-resistant. However, prolonged exposure to strong acids can cause fiber structural deterioration.

Alkali: Banana fibers are resistant to alkalis. Although they are rather stable in alkaline circumstances, prolonged exposure to high alkalis may harm the fibers.[120]

Oxidizing Agent: Banana fibers are susceptible to oxidizing chemicals, which can cause color changes and deterioration.

Banana Fiber Reinforced Polymer Composites

A composite material is a macroscopic combination with an identifiable interface between two or more distinct continuous and discontinuous intermediate components. A composite material can have beautiful and unique mechanical and physical capabilities because it combines the most appealing characteristics of its elements while removing the least appealing. The properties of the component elements, as well as their distribution and relationship, determine the characteristics of a composite. Green composite materials are those materials which are developed from natural resources and these materials have very little contribution towards environmental pollution.[121]

Natural fibers have received significant attention in recent decades as a suitable reinforcement in polymer composites due to their benefits over traditional glass and carbon fibers. As they are less expensive, bio-degradable, renewable, and cause no risk to health. Furthermore, natural fiber-reinforced composites are believed to have strong future potential as a replacement.[121-123] The materials are not only useful in the fields of materials packaging, automotive, energy, and sports, but they are also suitable for biological applications such as implants and medical devices.[124]

Epoxy-based banana fiber composites (E/BF)

Epoxy resin is a costly resin. As a result, it has excellent mechanical and chemical features such as high strength, rust resistance, strong adhesion, and a variety of other properties.[125] It is resistant to both moisture and chemical attack. It has excellent electrical insulating characteristics and is free of volatile substances. They may be cured at room temperature without applying any pressure using a curing substance, or they can be heat cured. They can bind to almost any substance, including wood, glass, natural fibers, and metal. After curing, they show no or little shrinking.[126]

The composites were made using (epoxy resin, grade 3554A, and hardener grade 3554B). These two components were completely combined and stirred at low speed until a homogeneous matrix was formed. Banana-woven fabric was laid on the matrix layer.[127, 128] It was coated by another layer of matrix by gently pouring the liquid over the surface of the fiber woven fabric to avoid air trapping. The three-layered composite was allowed to dry at ambient temperature.[128] The operation was repeated until the necessary thickness and fiber weight were produced.[127] As shown in the sample in **Fig 13**.[128]

Figure 13 Pseudo-stem banana Fiber reinforced epoxy composite during the curing process

Under the given study circumstances, 15 wt% banana fiber reinforcement was the best suited for reinforcing the epoxy matrix.[127] The applied stress is transmitted and distributed to the banana fiber by the epoxy matrix, resulting in increased strength by 90% compared to virgin epoxy. As a result, the composite can withstand larger loads before breakdown than unreinforced epoxy. Furthermore, greater maximum tensile strength and elongation result in greater material hardness. Flexural strength also increased in banana fiber composite than in epoxy alone.[128, 129]

The impact strength test findings revealed that the pseudo-stem banana fiber increased the impact strength qualities of the virgin epoxy material by around 40%. stronger impact strength values result in stronger material toughness qualities.[128] The E/BF composites have a low percentage of water absorption.[129]

Polyethylene-based banana fiber composites.

Banana fiber (BF)-filled composites based on high-density polyethylene (HDPE)/Nylon-6 blends were created using a two-step extrusion process.[130]

In the presence of styrene triblock polymer, the results revealed that HDPE mixed with Nylon-6 had higher strength and modulus than simply banana fiber-based HDPE. When the weight percentage of banana fiber was increased to 48.2% while the weight ratio of maleic anhydride grafted polyethylene remained constant, the flexural strength and modulus of the composite increased but toughness steadily declined.

Styrene triblock polymer also improved fiber reinforcing in the matrix. The water absorption capacity of the composite increases as the banana fiber weight increases and Nylon-6 with styrene triblock polymer is added.[131]

Polyester-based banana fiber composites

Previously, we have shown that banana fibers are an efficient reinforcement in a polyester matrix. The surface of the banana fiber was first treated with various concentrations of alkali, and the treated fiber was utilized to make composites.

Secondly, the fabric was treated with silane. Depending on the silane employed, an ethanol/water combination was created, and the pH of the solution was kept at 4 by adding acetic acid. Banana fibers were carefully dipped in the previously mentioned solution and were left to dry in the air.[132]

In the third stage, the acetylation of banana fiber was done by submerging it in an acetic acid/acetic anhydride combination with sulphuric acid as a catalyst. Following that, the fiber was separated from the mixture, rinsed with distilled water until all unreacted chemicals were removed, and lastly dried at room temperature. The acetylation of banana fiber to improve the hydrophobicity and oil absorbency.[133]

The fiber was coated with polyester resin, to which 0.9 volume percent cobalt naphthenate and 1% methyl ethyl ketone peroxide were added, and the air bubbles were gently removed with a roller. The pressure was kept on the closed mold. The samples were cured at room temperature before being removed from the mold. The demolded samples were post-cured at room temperature for an additional amount of time.[134]

Treatment with NaOH aids in the removal of cellulose particles with a low degree of polymerization. The elimination of low cellulose fractions and adhesive ingredients results in improved packing of the cellulose chains following the breakdown of the cementing ingredient, lignin. The alkali treatment increased the mechanical characteristics (tensile and flexural properties), and the treated composites were stronger than the untreated composites. The effect of alkali treatment is shown in **Fig 14.**[135]

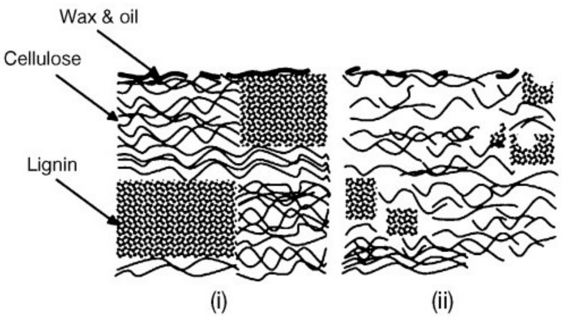

Figure 14 Typical structure of (I) untreated and (ii) alkalized cellulose Fiber.

Banana fiber was treated with Silane coupling agents, which have been utilized effectively with fillers and reinforcements containing a reactive OH group on the surface. The impact of the silane's organofunctional group is determined by its capacity to react with the polymer matrix. Silane treatment has also enhanced the composites' mechanical characteristics.[136]

Polylactic acid /banana fiber-based sustainable bio-composites

Polylactic acid (PLA) is a biodegradable, linear aliphatic thermoplastic polyester produced by ring-opening polymerization of cyclic lactide dimers or condensation of lactic acid. It is a promising polymer with basic biodegradability and an adequate lifetime to retain mechanical qualities without quick hydrolysis. This highly crystalline polymer with transparency can be used in a variety of applications. The material offers high aesthetics and strength, as well as easy processing.[133] However, the low thermal deformation temperature and expensive price of PLA now limit its utilization, prompting significant attempts to overcome the polymer's limitations.[137]

Before compounding, treated or untreated banana fibers, and PLA were pre-dried in a vacuum oven. Following that, the fiber and PLA melt were combined in a single mixer. Before compression molding, the melted mixture was cooled to room temperature. Finally, the thickness of molded sheets was made using a compression press. Then, samples were made from these sheets as previously.

Bio-composites with 20%- 30% fiber have superior mechanical characteristics.[138] With the addition of 30% BF, the stiffness of PLA increased by 31%. Tensile strength and modulus increased in surface-treated BF bio-composites, indicating better contact interaction between the fibers and the matrix. Si69-treated fiber composite exceeded all other surface-treated fiber bio-composites in terms of thermal stability. Surface-treated fiber-reinforced bio-composite exhibit high storage moduli, demonstrating a stronger bond between treated banana fiber and polymer matrix. When placed in a bacterial medium, all the bio-composites degraded by 80-100%. Fiber surface change influences microbial activity. As a result, PLA/BF bio-composites may be efficiently employed for a variety of end-use applications at appropriate fiber and polymer concentrations and coupling agents.[133, 139] As shown in **Fig 15.**[137, 140]

Banana Fiber-reinforced poly lactic acid composites have high availability, low cost, and strong mechanical qualities, allowing them to be utilized to create lightweight materials for application in the automotive and home sectors.[138]

Conclusion

This review explored the importance of banana pseudo-stem fiber, extraction methodologies, features, and numerous surface modification methods.

Banana fiber is largely made of cellulose, hemicellulose, lignin, and pectin, with cellulose acting as the primary component. For fiber extraction, mechanical extraction using decortication is preferable. Degumming is an optional process to increase the fiber's quality. Fibers are frequently changed using chemicals or enzymes to meet specific needs, such as producing composites or improving processability. Surface treatments remove non-cellulosic elements from the fiber, resulting in better characteristics. Besides this, banana fiber can be reinforced with polymer composites such as epoxy, polylactic acid or polyester, etc. Because it combines the most desirable qualities of its constituents while discarding the least appealing, that led to amazing and different mechanical and physical capabilities.

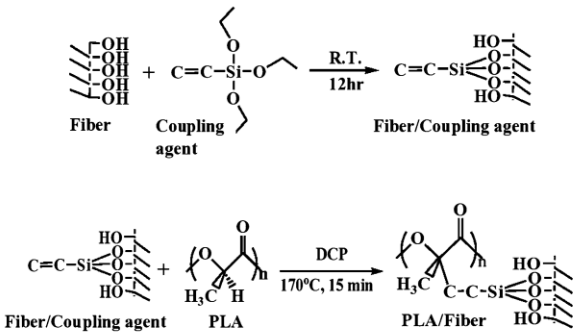

Figure 15 The reactions of **a** coupling agent and Fiber **b** PLA and modified Fiber

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Conflict of Interest

The authors declared no competing interests in the publication of this article

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استخدام ألياف السليلوز المتجددة (ألياف الموز) في تطبيقات المنسوجات المختلفة ومركبات البوليمر المقوية

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المستخلص

تُشتق الألياف من الموارد الطبيعية وهي سلعة مهمة تستخدمها صناعة النسيج. عند النظر في العرض الحالي والطلب المستقبلي، فإن إعادة استخدام النفايات الزراعية وتحويلها إلى ألياف يعد خيارًا صديقًا للبيئة وجذابًا قد يساعد في تقليل التلوث البيئي وجعل صناعة النسيج أكثر استدامة.

لقد شرحنا في هذه المراجعة العديد من المصادر الثانوية المحتملة لإنتاج الألياف، مع دراسة حالة تتعلق بالكتلة الحيوية المتبقية لنبات الموز، وهي نفايات زراعية رئيسية في العديد من الدول النامية. يتم التعرف بشكل متزايد على ألياف جذع الموز الزائفة، التي تتمتع بصفات فيزيائية وميكانيكية استثنائية، كمواد نسيجية أساسية. بسبب محتواه العالي من السليلوز، وقوة جيدة إلى متوسطة، ونعومة، ونسبة طول الألياف إلى التنفس، وخصائص أخرى. وتستخدم ألياف الموز في مجموعة متنوعة من الصناعات، بما في ذلك المنسوجات والمواد المركبة والسيارات. علاوة على ذلك، يمكن استخدام ألياف الموز في صناعة الملابس مثل الفساتين والقمصان والسجاد، وكذلك الحقائب وحقائب اليد والمحافظ والأحزمة والأحذية وما إلى ذلك. يمكن أيضًا استخدام ألياف الموز كمركب بوليمر مقوى، والذي يتم استخدامه بسرعة في مجموعة واسعة من التطبيقات لأنه يوفر بديلاً صديقًا للبيئة وفعالاً من حيث التكلفة للمواد التقليدية المشتقة من النفط بالإضافة إلى خصائصه الفيزيائية المحسنة.

الكلمات المفتاحية: السليلوز المتجدد، ألياف الموز، مركبات البوليمر المقوى.