Review Article

Polymers from
Renewable Resources

Polymers from Renewable Resources
2023, Vol. 0(0) 1–19

DOI: 10.1177/20412479231173113
journals.sagepub.com/home/prr
Sage

Fiber-reinforced polymer composite: Higher performance with renewable and eco-friendly plant-based fibers

Nurhania Nurhania, Syarifuddin Syarifuddin, Bidayatul Armynah and Dahlang Tahir

Abstract

Considering sustainable environmental problems due to waste and the enormous potential of natural plant resources in producing natural fibers has encouraged researchers to make environmentally friendly composite materials reinforced with fibers. Several articles on using natural fibers as composite reinforcement have been collected and studied to produce this article. This article aims to comprehensively describe the physical properties, chemical composition, factors that affect fiber quality, and their relationship with mechanical properties. In the first section, we introduce the general classification of plant fibers and summarize the annual production and category of fiber origin used for fiber-reinforced composites. It then presents the parts of plants and plant species for fiber, including fruit, leaf, and seed fibers, and discuss their characteristics. Further describes the chemical compounds and physical and mechanical properties based on fiber sources. Based on our discussion, this review shows that plant fibers are very suitable as an alternative to polymer-based reinforcement materials due to low cost, renewable, and environmentally friendly composites. However, compatibility with synthetic polymers, dimensional stability and processability must be actively considered to replace synthetic fibers in various applications.

Keywords

Natural fiber, physical properties, chemical properties, mechanical properties, fibers reinforced polymer, renewable, environmentally friendly applications

Received 11 January 2023; accepted 15 April 2023.

Department of Physics, Hasanuddin University, Makassar, Indonesia

Corresponding author:
Dahlang Tahir, Department of Physics, Hasanuddin University, Kampus Tamalanrea, Makassar 90245, Indonesia.
Email: dtahir@fmipa.unhas.ac.id

Introduction

The number of environmental problems increased, consequently increasing the number of community consent or scientist interest in using environmentally friendly materials such as natural fiber.[1] The industry worldwide since 2000 started using natural fiber-reinforced polymer composites for various applications including, civil and automotive industries.[2–7] It will increase yearly by about 10%.[8] The increased interest in using natural fibers in solving environmental problems is inseparable from their advantages: low density, high specific properties, low cost, non-abrasive to processing equipment, and most importantly, biodegradability.[9,10]

Natural fibers took from plants or animals,[11] such as oil palm, sisal, flax, jute, camel hair, and sheep wool. The fibers from the part of plants are classified into bast fibers such as jute, flax, ramie, hemp, kenaf, seed, cotton, coir, kapok, and leaves such as sisal, pineapple, and abaca, grass, and reed fibers such as rice, corn, and wheat, and core fibers examples: hemp, kenaf, and jute, and other kinds of fibers such as wood and roots.[12,13]

Plant fibers contain a high amount of cellulose to form framer fiber. All parts of the plants are single-cell fibers, except the seed is the ultimate fiber. The characteristics of fibers are high flexibility, fineness, and a high length ratio to thickness.[14,15] The cellulosic fibers can be used directly for textiles.[16] for clothing and other purposes without additional chemicals.[17] In the last decade, fibers were put into bricks to form fiber-reinforced pottery.[18] Ref.[19] was reported that hemp fibers in 1930s was applied to BMW and Mercedes car components.

According to Ahmad's research, manufacturers are increasingly interested in using plant fibers in the core structure of composite materials to meet rising customer demand for sustainable features with improved mechanical performance and usefulness.[20] In this review, we aim to systematically review the type of fibers and describe the chemical, physical, and mechanical properties organized as follows We first introduce the classification of plant fibers in general and summarize the annual production and category of fibers origin used for reinforced composite fibers. We then present part of the plant and plant type for fibers, including Fruit, Leaf, and Seed fibers, and discuss their characteristics. We described the chemical compound and physical and mechanical properties based on the sources of fibers. The last chapter reinforced composite fibers as promising applications of fibers in various industries. In conclusion, we offer an outlook on fibers, perspectives, and challenges of the future development of reinforced fibers. Natural fiber-based composites have been widely produced and used for interior components in the automotive and aerospace sectors. Natural fibers are also used to make insulation materials for a variety of applications, including blowing insulation, pouring insulation, impact sound insulation materials, and ceiling panels for thermal insulation and acoustic isolation.[21] Natural fiber composites have a promising future, even outperforming current materials.

To quickly identify the environment, the visual image of some fiber sources, including the classification of source fibers, can be seen in Figure 1. Table 1 shows the classification of the selected plant fibers, the world annual production, botanical name, and part of the plant or plant origin. Cotton fiber is the most abundant, followed by bamboo, Jute, and kenaf, respectively, while abaca fiber is the least abundant. The most widely used plant origin or plant part in the manufacture of stalk fiber is obtained from the stems of dicotyledonous plants and is used for textiles and ropes.

Fiber types

Fibers naturally organize into bundles from the bast stem, leaf, and fruit called fiber bundles. However, fibers from seed are single cells referred to as fibers.[34] The ginning process separates

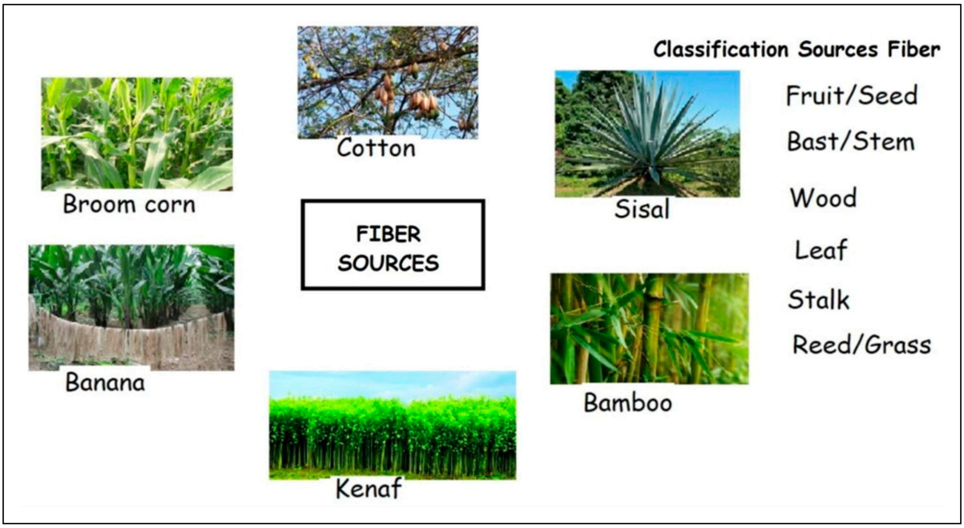

Figure 1. Visual image of some sources of natural fiber from author collection and from the open sources in social media.

Table 1. Fiber of plant and corresponding botanical name, plant origin, and world annual production from various references.

Fiber type	Botanical name	Plant origin	Production (10^3 Tones)	[Source]
Abaca	*Musa textilis*	Leaf	91	22–24
Bagasse	*Saccharum officinarum L*	Stem	102	22,24–27
Banana	*Musa ulugurensis Warb*	Leaf	200	22,24,27
Bamboo	*Gigantochloa scortechinii Dendrocalamus apus*	Stem	10,000	24
Coir	*Cocos nucifera* L.	Fruit	650	23,25,28,29
Cotton	*Gossypium* spp.	Seed	19,010	23,24
Flax	*Linum usitatissimum*	Stem	830	23,24,30–32
Hemp	*Cannabis sativa L*	Stem	214	23,24
Jute	*Corchorus capsularis, Corchorus olitorius*	Stem	2850	23,24,32
Kapok	*Ceiba pentandra*	Seed	123	29
Kenaf	*Hibiscus cannabinus*	Stem	970	23,24,32
Phormium	*Phormium tenax*	Leaf	-	33
Pineapple	*Ananas cosmosus Merr*	Leaf	-	29
Ramie	*Boehmeria nivea Gaud*	Stem	100	23,32
Sisal	*Agave sisilana*	Leaf	318.8	23,24,28,32

fiber bundles from seed, especially cotton lint, while kapok fibers by shaking for loose from the seed. Decortication and retting techniques are separate fiber bundles from the leaf and bast of fiber plants. A decorticator is a machine used to strip fibers bundles from the stem or leaves crushed and beaten by a rotating wheel where only the fibers remain. The other parts of the leaf are washed away by water-decorticated fibers and then washed before drying in the sun or using hot air.[35]

Retting is a chemical or biological treatment for separating or removing fiber bundles more easily from the wood.[36] There are two traditional types of retting: dew and water retting. Dew retting is monitoring to ensure that bast fibers separate from the core without much deterioration. This method is most prevalent in Europe, but some countries in Asia also mean that depending on the geographical location but produce coarser and lower quality fibers than water retting.[37] Water retting entails the soaking of stems in water indicated requires a large amount of clean water and is consequently more expensive. However, the result is high-quality fibers that produce water fermentation waste. The chemical properties of the plant fibers as shown in Figure 2, including history and related discussion. Figure 3 shows factors affecting the quality of plant fiber, such as fiber extraction, supply from storage to transportation, age, plant growth including species, location, climate, and harvesting. The relationship between fine structure and mechanical properties is presented. Recent developments in plant fiber-reinforced composites are also discussed.

Fruit fiber

Coir fiber name derived from the Malayalam kayaru, ‘cord’[38] which is grown in the Indo-Malaysian region, East and Western African countries, and Central and South America. It is obtained from the fruit of the coconut palm and the fibrous tissue, which have three types of coconut fiber: the longest and the finest called ‘white’ fiber, a coarser fiber known as ‘brittle’ fiber, and a shorter staple fiber known as ‘mattress’. The brittle and mattress fibers are usually called ‘brown’ fibers.[39] The retting process is traditionally employed to extract coir fiber bundles where the husk is immersed in water for 3–9 months. Then continue with a decorticating process to separate the fiber bundles, one of the key factors affecting the quality of fibers. Some factors affect the quality of fibers, including species of plant, harvesting process, fiber extraction, supply transportation, storage conditions, and age of fiber, as shown clearly in Figure 3.

Leaf fibers

Abaca fiber is the most important species and then bears the edible banana fruit, which produces high-quality fibers. The leaf fibers as hard are obtained from the stalks of various monocotyledonous plants with parallel-veined leaves and one seed leaf.[40] The fibers are in bundles of individual cells of the leaf sheaths. They can remove from the strands by boiling them in an alkali solution. The fiber lumen is more significant compared with that of the cell wall. Banana fiber Musa paradiisiaca L. var Sapientum or Musa ulugurensis is the most cultivated banana plant.[27] There are about 300 species of banana but only 20 species for consumption. The plants are cut at the flowering stage to obtain the best fiber before forming any fruit. The separation process is manual. It involves cutting pieces of banana from the stem and passing them through a mangle to remove excess moisture (water) and drying at ambient temperature. The fiber obtained is usually low quality because of the separation of the fiber bundles after the fruits have just developed or when they have ripened and are ready for food purposes.

Phormium, or New Zealand flax, was one of the early primary fibers uses in Europe but was usually used for ornamental purposes. It is extracted mechanically by hand prepared and woven into cloth resembling linen.

Pineapple plants are grown in tropical America, Far-East Asia, and Africa. In the Philippines, India, and Taiwan, the pineapple plant is used mainly as a source of fiber. The pineapple fiber bundles are separated from the pineapple leaf by hand and sometimes by machines involving stripping the fiber from the retted leaf. The use of machines to separate the fiber bundles is slower

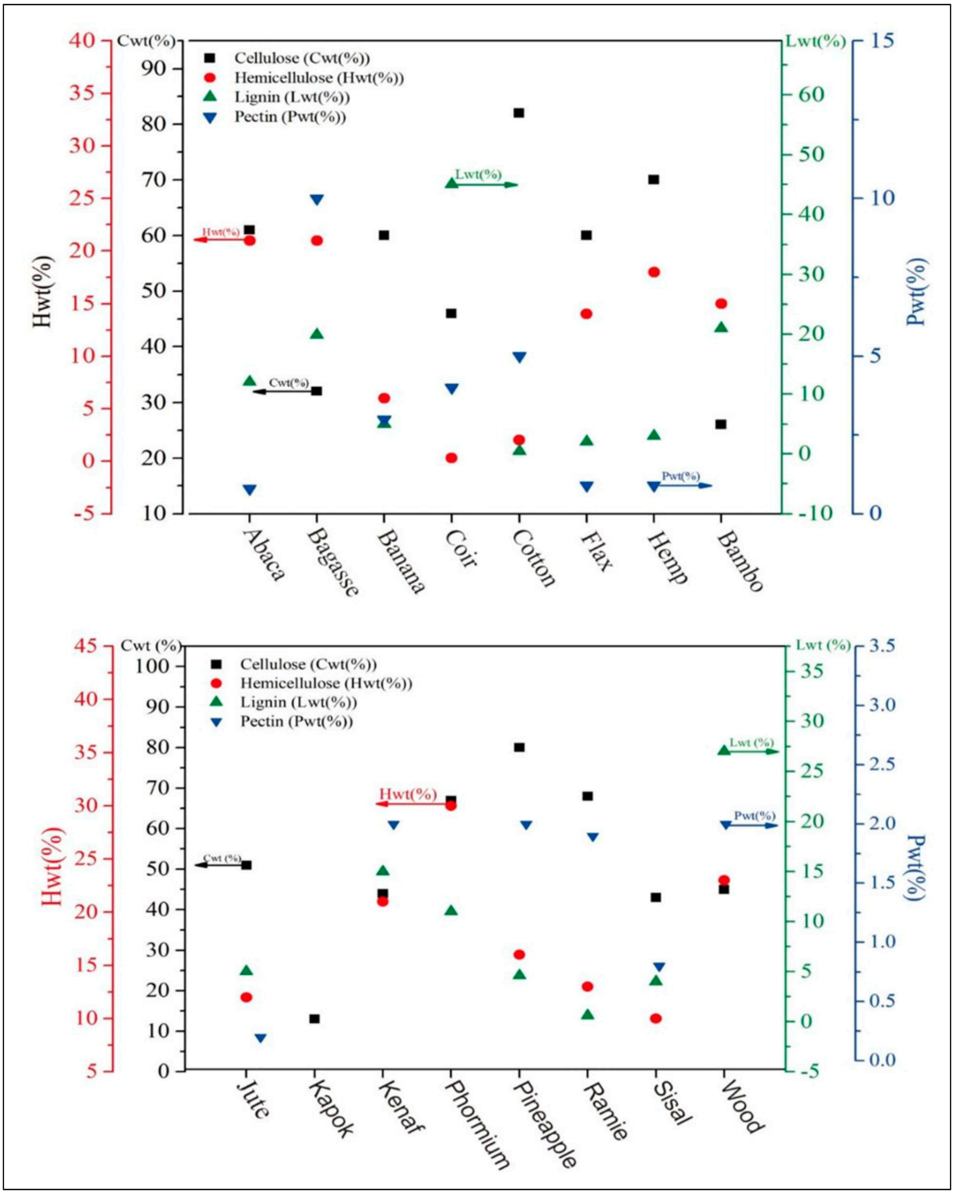

Figure 2. Chemical composition of the plant fibers: cellulose (C wt %), hemicellulose (H wt %), lignin (L wt %), pectin (P wt %). The data Abaca taken from.[51] Bagasse,[52] Banana,[53] Bamboo,[49] Coir,[54] Cotton,[55] Flax,[56] Hemp,[57] Jute,[58] Kapok,[59] Kenaf,[60] Phormium,[33] Pineapple,[61] Ramie,[62] Sisal,[60] and wood.[63]

than the hand extraction method but facilitates mass production processes. This method is laborious and costly and tends to lose many weaker fibers. Hand-separated pineapple fiber bundles yield 2%–3% dry fiber, about 1 ton of pineapple leaf.[41]

The agave genus includes sisal, a semi-xerophyte plant practically without a stalk, which is significant sisal growing in Brazil, Tanzania, and Kenya.[19] Sisal is distinguished from abaca by

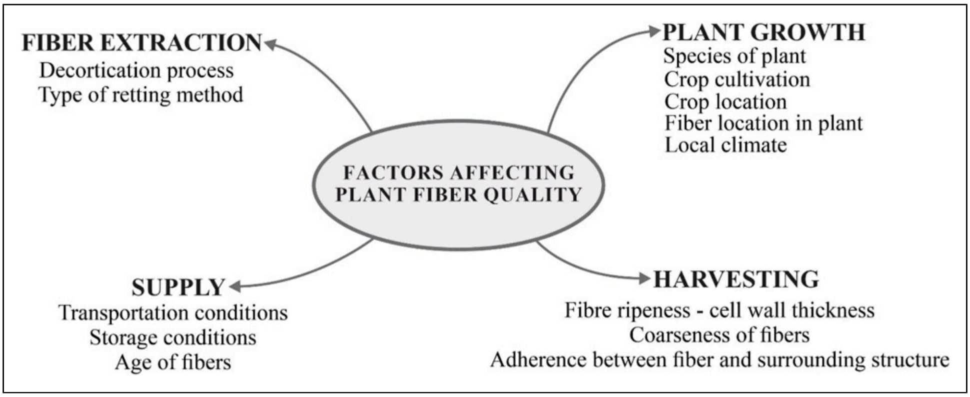

Figure 3. Factors affecting quality of plant fibers; fiber extraction (type of retting methods), supply (from the storage to the transportation, and age), plant growth (species, location, and climate), and harvesting (fiber refines, adherence, and coarseness).

Billingham's test and the presence of rodlike crystals in the ash and differs from phormium fiber. The ultimate fibers are polygonal in outline with a rounded structure of lumen when viewed in cross-section. The lumen varies in size but is usually significant. The longitudinal shape is approximately cylindrical with a blunt tapering tip similar to abaca.[38]

Bast fibers are from the stems of various dicotyledonous plants. They are also referred to as soft fibers, which can be used to distinguish them from leaf fibers. Dicotyledonous plants have two seed leaves and are synonymous with phloem, the food conducting tissue of vascular plants. The phloem fibers were obtained from the cortex and pericycle. Bast fiber bundles are composed of elongated thick-walled cells joined together both ends to end and side by side and arranged in bundles. Bast fiber bundles are removed from the host material by decorticating, which consists of removing from the stem the 'cortex' comprising the bast and outer barks. The separated fibers were then washed in the water and then dried. Bamboo has a hollow stem called the culm, with the cellulose fibers aligned along the length of the culm carrying nutrients between the leaves and roots with light-colored lignin. Bamboo can be grown in both the tropics and non-tropic. There are about 1250 species of bamboo and over 10.000 tonnes are produced annually,[32] which are used as the primary building materials in developing countries.

Flax can be grown and harvested periodically every 3 months with a long plant of about 900–1200 mm and a wide of 1.5–3 m. For harvesting, before lignification takes place will result in poor quality fiber. However, early harvesting produces a low yield of fiber. The number of fiber bundles in the stem ranges from 15 to 40, and each bundle contains between 12 and 40 ultimate fibers. The ultimate fibers consist of cells with very thick walls and very small lumens. Unlike other bast fibers, Flax contains transverse dislocations.[42]

Hemp is a temperate climate plant grown mainly in Russia and Eastern Europe.[16] In contrast to industrial hemp, planted only centimeters apart, with most of its leaves concentrated at the top, the marijuana plant is quite dense, leafier, shorter, and bushier. Hemp fibers were used to manufacture 90% of all ships' canvas sails, rigging, nets, and caulk due to their specific strength and resistance to salt water. It is reported that the hemp plant produces about 0.168 kg of fiber per square meter. In contrast, the cotton plant produces only 0.057 kg of fiber per square meter. Hemp does not need the enormous amount of agricultural chemicals that cotton needs to grow.[16]

Hemp fiber bundles are separated from the stem in a decortication process by the cut or pulling from the ground. The cut plant is then retted, allowing the enzyme secreted by microorganisms to digest or degrade. The non-cellulose materials, mainly pectin, hold the fibrils together to liberate the fiber bundles.[43] The long bark fiber from the stalk can be spun into threads, made into ropes, and woven into fabrics, carpets, and shoes. The inner core of the stalk can be made into dioxin-free paper and pulp, as well as charcoal, methanol, and methane. The latter are biomass fuels, which are clean and virtually free from pollutants generated by the combustion of fossil fuels.

Jute is the second most crucial fiber, fast-growing in hot and humid climates, with a height of about 2.5–3 m within 4–6 months.[2,41] Jute is harvested when about 50% of plants are in the pod for high-quality fiber bundles. The fiber bundles are separated from the woody stem by the retting process. About 10,000–14,000 kgs of green plant yield from 4.5–8% of their green weights in dry fiber plant stem in the form of an annular meshwork composed of more than one fiber layer. Jute is the most widely produced of the bast fibers, followed by flax and hemp fibers. It has a higher lignin content, distinguishing it from flax and hemp fibers.

Kenaf has been cultivated and exploited as a source of fiber grown in tropical and sub-tropical Brazil. The bark fibers of the kenaf plant are long and stringy, but the inner core is much like balsa wood. Kenaf can produce about 2.47 kg of pulp per season, the same amount a pine tree can produce after 20 years of growth.[16] The application of kenaf fibers can be found in markets using building materials such as fiberboards, fire, and root proof.

Ramie is grown in Brazil, India, Japan, South-East Asia, Southern Europe, and Chinese.[42] and can be harvested 3–6 times a year. The highest yield is attained in the third and fourth years and maintained until the plant is about 6 years old.[44] Ramie fiber is easily identified by its coarse, thick walls, lack of twist, and striated surfaces.[41] The fiber is extracted from the green plant by decorticating and possibly by degumming treatment with alkali to separate the fiber from the primary material.

Seed fibers

The essential seed fibers are cotton formed from a single biological cell and more than one cell growing the fibers. Cotton is mainly grown in tropical regions, and the maturity is analyzed by assessing the shape of the wall-thickness compared to the size of the lumen.[45]

Kapok (*Ceiba pentandra*) reached Java by the 10th century from west Africa, India, and the Far East[46] with three varieties: Var. Caribaea, Var. Guineensis, and sighVar. Pentandra.[47] The report from India, Kenya, Tanzania, and Thailand exported nearly 12,000 tonnes of kapok fiber per year.[42]

Figure 2 shows the chemical composition of some plant fibers, with the primary constituent cellulose, followed by hemicellulose, lignin, and pectin. Fibers from cotton show the highest cellulose in between 82 to 96 wt % ,[48] followed by pineapple, around 80–81 wt %, and the lowest is kapok (Yang et al., 2020) followed by bamboo.[49] Cellulose is also the reinforcement for lignin, hemicelluloses, and pectin.[50]

The plant fiber quality depends not only on the chemical composition (Figure 2) but also on the several factors shown in Figure 3. Four factors affect the quality of plant fibers; first, fiber extraction strongly depends on the type of retting methods. Second, the supply methods from the storage to the transportation and age of the plants. The third is plant growth, including the species, location, and local climate around plant growth. The fourth is harvesting, such as refines, adherence, and coarseness.

The physical properties such as diameters, length, aspect ratio, microfibril, bulk density, and moisture regain from various types of fibers. Fibers with the highest aspect ratio will exhibit the highest tensile properties and provide a high surface area advantageous for reinforcement purposes. Figure 4 shows the physical properties of fibers from leaf and bast fibers.

Physical properties of plant fibers

Fruit, leaf, and bast fibers are usually separated from bundles of fibers, and the length of ultimate leaf fibers is between 2 to 60 mm .[42] Robson et al. [27] reported that the fiber bundle length is between 60 to 100 mm. That implies that several ultimate fibers are joined by natural binding materials such as lignin, wax, and pectin. Ramie is a bast fiber with lengths up to 250 mm (Figure 4). For optimum fiber treatment, chemical concentration must be lowest for prevent extra fibers delignification to avoid weaken and damage the fibers by decreased fiber but can increased effective fiber surface area and aspect ratio. The cross-section and longitudinal views from scanning electron microscopy (SEM) spectroscopy was reported by.[45] and.[64] for hemp and sisal fiber and shows the spiral annular vessels in the sisal, which are the nutrient pathways for the sisal leaf.

Gholampour & Ozbakkaloglu, 2020 was reported for untreated fiber bundles shows fracture surfaces of fiber composites indicated present wax, oil, and surface impurities. Waxes and oils provide a protective layer to the surface of the fibers. The surface fibers highly packed crystalline cellulose but changed when the amorphous regions created where cellulose are separated and filled by water molecules. For transversal cross-section was reported by indicated fiber bundles with a large lumen as reported by.[70] For untreated sisal fiber bundles,[45] node-like cell materials indicated adjacent ultimate fibers, but.[71] was reported for small and large lumens for every single ultimate fiber of hexagonal shape. For fiber treatment, the wax and cuticle at the surface was removed producing smooth fiber surface.

Coir is the reddish-brown fibrous mass, and the average length of the ultimate fibers is about 1 mm (Figure 4). The fiber bundle can have 30–300 or more ultimate fibers in its cross-section. The edges of some of the fibers have a distinct wavy outline, and they are spindle-shaped, lying along the fiber axis with the round stigmata to be found in the ash.[43]

The physical characteristics of cotton fiber are the most interesting. It has layer arrangements, as with all plant fibers. However, its unique helical fibril winding formation distinguishes it from other fibers. The winding formation of the fibril along the major axis tends to have an alternate reversal direction as it winds along the fiber axis.[72] The lumen of mature cotton fiber is filled with protoplasm.[73]

Kapok fibers are unicellular smooth, cylindrical, and very lustrous. They are in a pod of kapok fruit and grow on the inner wall of the pod and sometimes on the seed. The fibers are coated with a highly water-resistant waxy. It has a thin wall with an air-filled lumen which lustrous and extremely light. When viewed through its cross-section, kapok fibers show a wide air-filled lumen with a wall thickness of about 1–2 μm. For instance, the apparent specific gravity of the Indian kapok fiber is about 0.0554, while that of Japanese kapok is about 0.0388. It is also reported that kapok fiber is six times lighter than cotton water repellent and slippery.[54] If kapok fiber is compressed, it can support, on water, a mass that exceeds its mass by as much as similar or beyond twenty times. After submerging, Kapok fiber will lose its buoyancy capacity very slowly.

Mechanical properties of plant fibers

The fiber cell wall consists of the outer layer, which has the primary wall and the cuticle; the secondary wall consists of three layers, S1, S2, and S3, which connect the secondary wall to the lumen Figure 3(a). The S1 is next to the primary layer, known to resist swelling media such as water

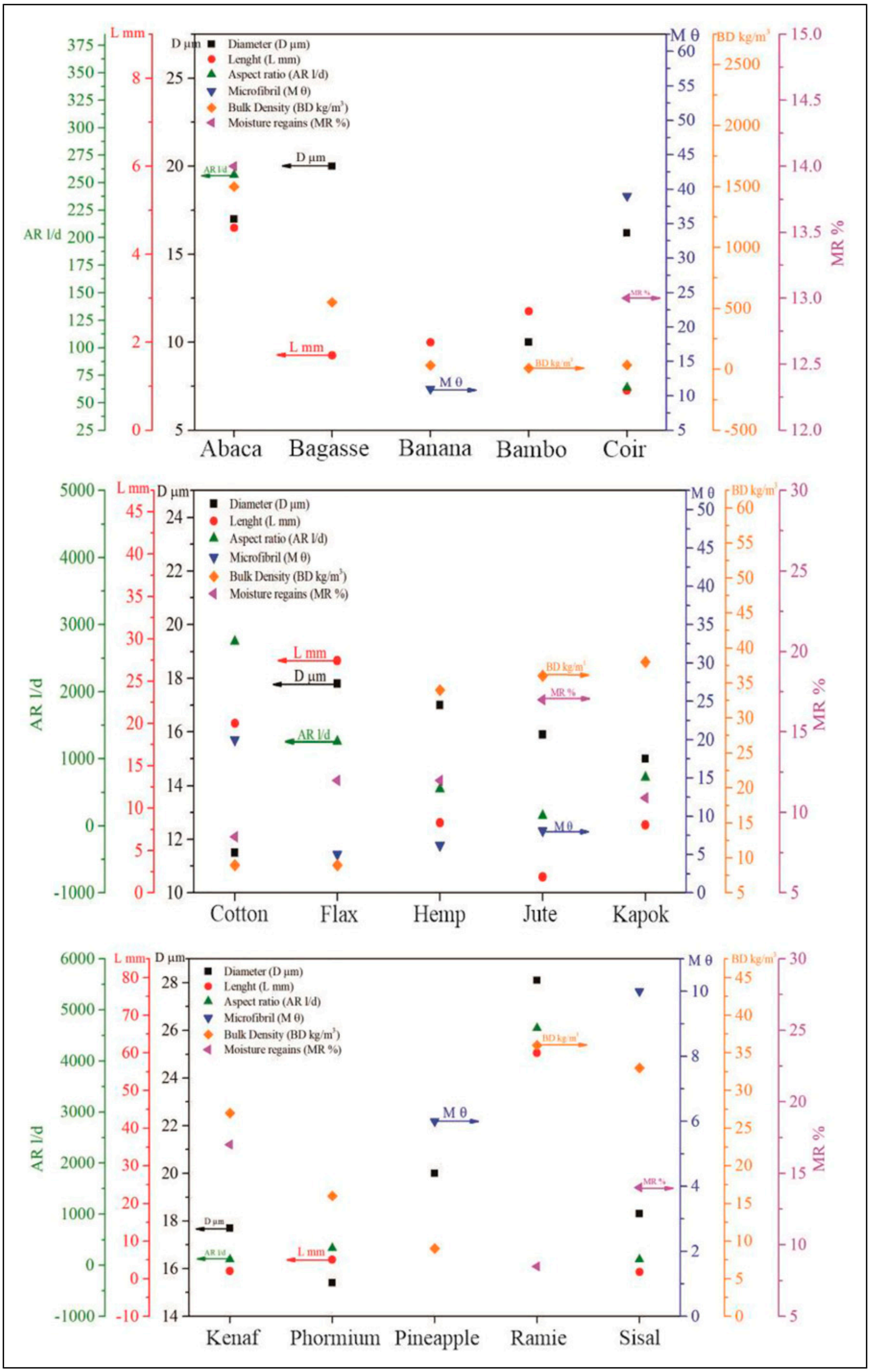

Figure 4. Physical properties of the plant fibers: diameter (D µm), length (L mm), aspect ratio (AR l/d), microfibril angle (M θ), bulk density (BD kg/m^3), and moisture regain (MR%). The data Abaca taken from.[51] Bagasse,[24] Banana,[39] Bamboo,[49] Coir,[64] Cotton,[62] Flax,[65] Hemp,[66] Jute,[52] Kapok,[59] Kenaf,[67] Phormium,[33] Pineapple,[68] Ramie,[62] and Sisal.[69]

and acetic acid, just like the primary wall.[71] The fibrillar structure layout in this layer is nearly perpendicular to the fiber axis and stabilizes the fiber to lateral forces.

The S2 layer constitutes the bulk of the secondary wall and swells easily, breaking into fibrils that follow a helical path. The fibrils are inclined at an angle to the fiber axis and dominate properties in tension.[70,71] In cotton, the fibrils in the S3 layer are inclined more transversely to the fiber axis than in the S2 layer. They tend to resist the hydrostatic pressure exerted on the lumen. They are in the plant source or when using applications such as composites for industrial applications. The fibrous materials are subjected to the deformations such as tension, compression, bending, torsion, shear, abrasion, wear, and flexing.[39]

Plant fibers are composites in nature with cellulose as the reinforcement in a matrix of lignin and hemicellulose. Physical properties of fibers such as morphology, regularity, or irregularity along and across the main fiber axis, crystalline packing order, amorphous content, and chemical composition influenced the mechanical properties. The mechanical properties (Figures 6 and 7) can be predicted by using equation (1) to estimate the stiffness or modulus of elasticity of the plant fiber cell wall [63, 64, 65,66] along the fiber axis.

$$E_f = V_c E_c Cos^2\theta + V_{nc} E_{nc} \tag{1}$$

where, E_f is the effective modulus of the fiber, Ec and Enc are the elastic moduli of the crystalline and non-crystalline regions, and V_c and V_{nc} are the volume fractions of crystalline and non-crystalline regions and θ is the microfibril angle.

Figure 5 shows the mechanical properties of leaf and bast fibers, and Figure 6 shows the mechanical properties of coir and seed fibers. Figure 7 shows that the pineapple fiber exhibits the highest specific strength and modulus, followed by flax and hemp fiber. It implies that the weight of pineapple, flax, and hemp fibers will be more suitable in composite manufacture due to the savings on weight economies over the rest of the fibers.[74] The same fibers exhibit high stiffness, which means that they are used to replace glass, carbon, and high-performance synthetic fibers such as Kevlar fibers. A similar argument can be expressed for composites in which the single-cell fibers as shown in Figure 5.

Applications of the plant fibers

Almost all fibers have similar conventional uses divided into three applications: apparel, household, and industrial. Apparel applications are dresses or clothing where cotton fiber dominates the market, followed by flax, hemp, and to a certain extent, kapok when in blends with cotton fiber. Household applications are curtains, upholstery, mattresses, quilts, coir, and almost all seed, leaf, and bast fibers are used in this category except bamboo fiber. Except for the kapok fiber, all the fibers are used as industrial materials. The most common uses are rope, shoes, sacks, carpets, fishing nets, paper, and paper felts.

For the last 20 years, there has been a high interest in using natural fibers as a reinforcement for polymeric materials.[34,46] That is stimulated by the environmental cost of manufacturing energy-intensive, synthetic fibers such as glass, carbon, and Kevlar. Two well-established products are Tufnol 6 F/45, an epoxy-cotton composite, and Tespa, a phenol wood fiber composite.[81]

Thermosetting polymer matrix and plant fiber composites find applications as electrical insulators (Tufnol 6 F/45), semi-structural applications, and wear parts. Many reported the poor mechanical strength properties of the two materials, indicating the necessity for further product optimization. At the same time, many claims have been made that on a weight basis, the

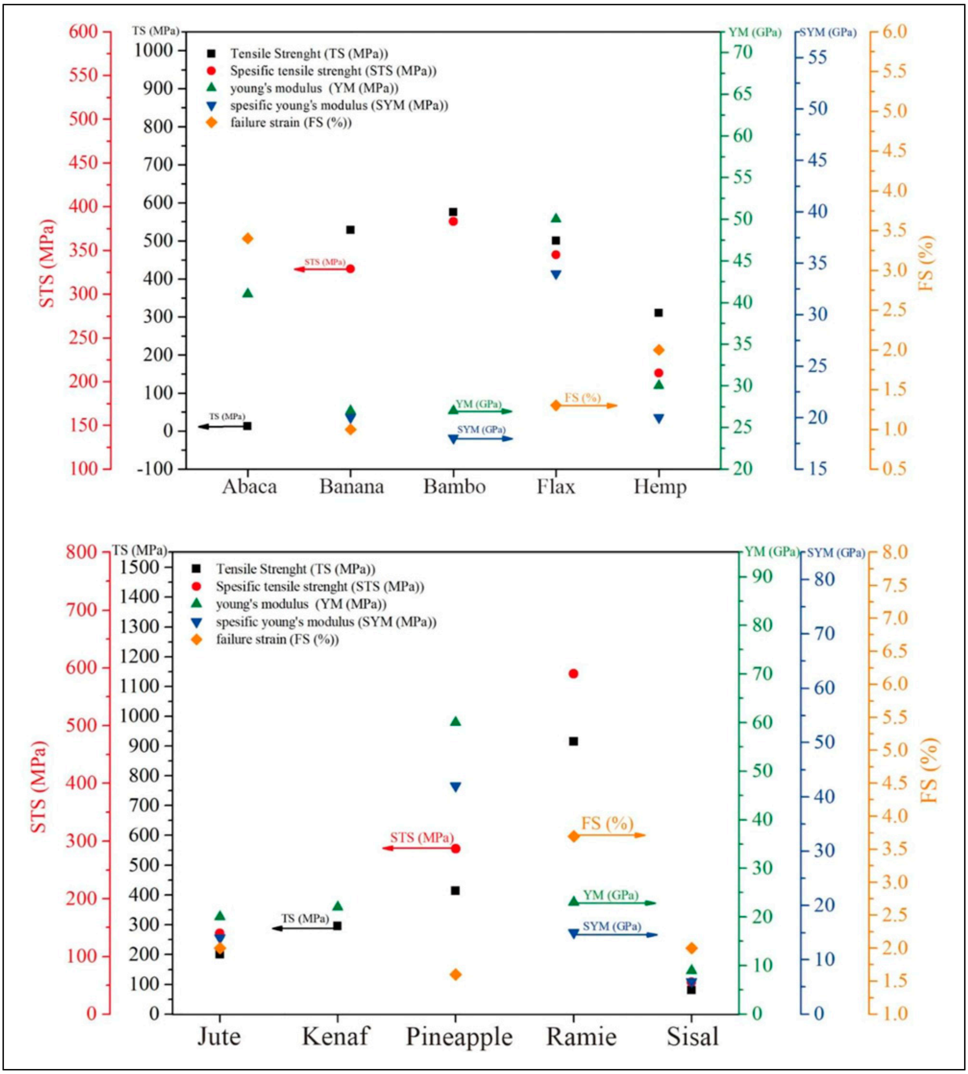

Figure 5. Mechanical properties of leaf and bast fibres: tensile strength (TS MPa), specific tensile strength (STS MPa), Young's modulus (YM GPa), specific Young's modulus (SYM GPa), and failure strain (FS %). The data Abaca taken from.[75] Banana,[40,75] Bamboo,[40,49] Flax,[22] Hemp,[76] Jute,[77] Kenaf,[40] Pineapple,[78] Ramie,[79] and Sisal.[80]

performance of the best plant fiber reinforced composites comparable with that of conventional glass epoxy composite. BASF AG produces lignotoc in sisal polypropylene composite.[81]; another prospective user of these plant fiber reinforced composites is the building industry. Figure 5 shows the mechanical properties of some plant fiber-reinforced composites.

Figure 7 shows composites sisal-cashew nut-shell liquid (CNSL) with the highest flexural stiffness compared with kapok-cotton fabric reinforced/CNSL and exhibits relatively good impact properties. Both bending and impact are preferred characteristics in the building and automotive industries.

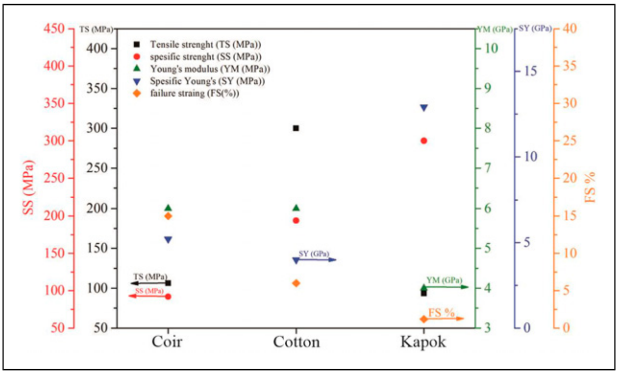

Figure 6. Mechanical properties of coir and seed fibers: tensile strength (TS MPa), specific tensile strength (STS MPa), Young's modulus (YM GPa), specific Young's modulus (SYM GPa), and failure strain (FS %). The data Coir taken from.[40] Cotton,[45] and Kapok.[77]

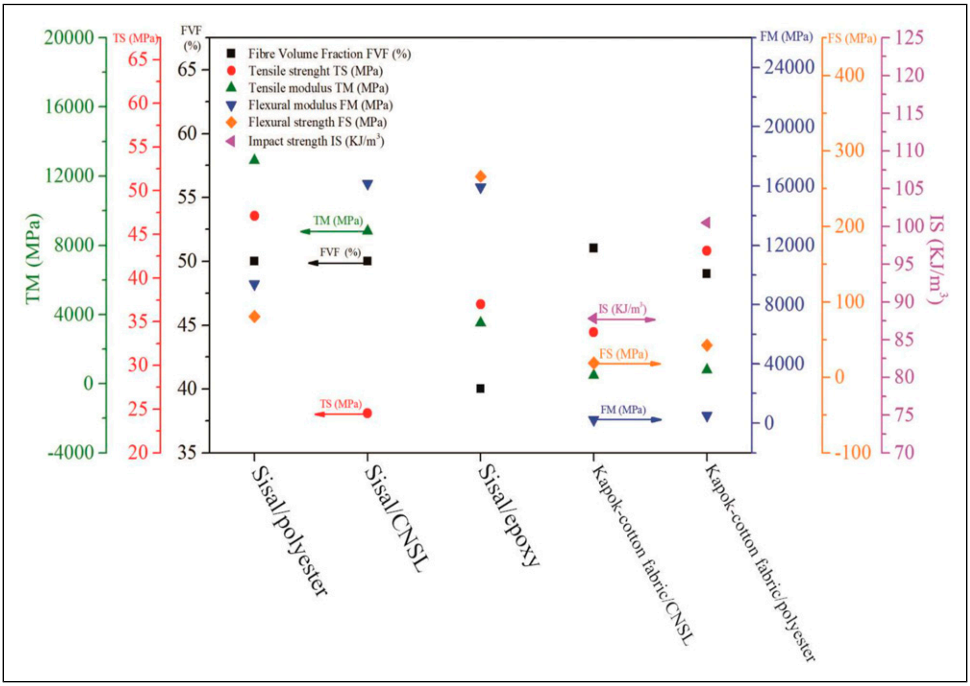

Figure 7. Mechanical properties fibers reinforce composite: fiber volume fraction (FVF %), tensile strength (TS MPa), tensile modulus (TM MPa), flexural modulus (FM MPa), flexural strength (FS MPa), and Impact strength (IS kJ/m^2). The data sisal/polyester taken from.[82] Sisal/CNSL,[83] Sisal/epoxy,[84] Kapok-cotton fabric/CNSL,[85] and Kapok-cotton fabric/polyester. [86]

Johnson Controls Interiors GmbH produces plant fiber-reinforced thermoplastics for interior parts of cars.[87] Prototype truck boards are produced from banana fiber reinforced composites[26,81] reports of successes in producing kenaf-polypropylene composites compare favorably with the glass polypropylene and mica-polypropylene composites. It is also worth noting that cellulosic is

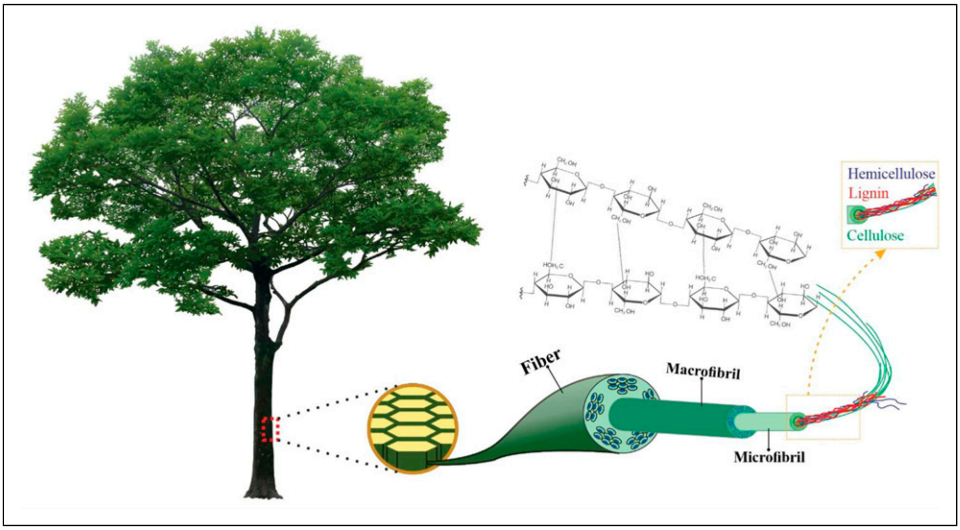

Figure 8. The hierarchical structure of wood is a natural fiber supply.

increasingly used as a biomass fuel source to produce energy for domestic and industrial applications.[88]

Future perspective

Natural fibers are not only good for the ecosystem, but they also have highly specific properties due to their lightweight nature. Trees are a readily available source of natural fiber, with large populations generating large amounts of yearly pruning byproducts, making them one of the most easily accessible sources of natural fiber. Fiber can be removed from the midrib, spadix stems, leaflets, and mesh of the date palm tree.[89] Wood has a porous hierarchical structure that spans the nanoscale of the cell wall to the macroscale of the trunk.[90] Wood's rigid cell wall is made up of three biopolymers: cellulose, hemicellulose, and lignin, which combine to create a natural fibril-based composite with properties determined by the orientation of aligned cellulose fibrils embedded within a matrix of lignin and hemicellulose.[91] Bundles of cellulose microfibrils contain both crystalline and amorphous areas and are made up of 3 nm elementary fibrils.[92] At the molecular level, repeating units of D-glucose assemble through covalent bonds as well as intra- and interchain hydrogen bonds to create linear and rigid cellulose chains.

Wood is made of various cell types with varying volume fractions at the cellular and tissue levels, depending on the tree species. Softwoods are made up of more than 90% of one type of cell (tracheid), with varying cell diameters and cell wall thicknesses based on their function.[93] Tracheids with large cell diameters and thin cell walls function as water transporters (referred to as "earlywood"), whereas tracheids with small cell diameters and thick cell walls function as mechanically robust tissues (referred to as "old wood").[94] Hardwoods evolved later and use cell types unique to these functions, namely vessels for water transport and fibers for mechanical strength, giving them a competitive advantage over softwoods in the majority of climate zones. The Lumina (exposed interior of the cell) of tracheids, vessels, and fibers (ranging in diameter from a few micrometers to about half a millimeter), along with micrometer-sized holes crossing the cell wall and nano-sized pores between cellulose fibrils within the cell wall, form the hierarchical porous structure of wood.[95] (Figure 8). Natural plants are the best option for use as source plants for fiber production because they are widely accessible and have the potential to replace synthetic fibers in the future.

Conclusions

Natural fiber composite has been intensively used recently due to increased car fuel efficiency, low cost, renewable, low density, high specific stiffness, better building materials, and being environmentally friendly. The lower density of the cellulose-based fibers leads to weight savings in composite manufacturing transportation. Natural fibers' biodegradability as a composite material makes them highly appealing because they are environmentally beneficial and abundant. The higher fiber volume fractions of plant fibers compared to fossil fuel-based reinforcements will result in significant material cost savings. Recently, natural fiber reinforced composites (NFRCs) have a growing interest among scientists because of their ease of production, increased productivity, cost reduction, lower density and weight, and use of renewable resources. Although increased interest, there are many problems associated with the quality and production of natural fiber-based composite materials, such as compatibility with synthetic polymers, dimensional stability, and processability. Composite materials should ideally match the interface even when applied stress. Due to the significant low weight and cost of the raw fiber materials, they have become attractive alternatives for replacing glass and carbon fiber reinforced polymer composites. The automobile industry has begun applying NFRCs in various exterior and interior panel applications. However, further research must be kept growing to address how to increase the quality source of fiber in extraction, transportation, and harvesting for maintain chemical and mechanical properties. These parameters guarantee mass production for the continuity of commercially available NFRCs for wide area application, especially in the automotive field.

Acknowledgments

Member of materials and energy Lab is gratefully acknowledged for helpful and discussion.

Authors' contribution

Nurhania Nurhania: literature search, Data curation, Writing - original draft. Syarifuddin Syarifuddin and Bidayatul Armynah: idea, literature search, Resources and editing. Dahlang Tahir: Conceptualization, Writing-original draft, Writing-review and editing, Resources, Supervision.

Declaration of conflicting interests

The author declare that they have no known competing financial or personal relationship that could have appeared to influence the work reported in this paper. The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Data availability

Data available from the authors upon request.

Informed consent

All authors consent to participating in this work. All authors agreed to the publication in the submitted form.

Ethical approval

The authors confirm that there were no ethical in preparing this manuscript

ORCID iD

Dahlang Tahir https://orcid.org/0000-0002-8241-3604

References

1. Peças P, Carvalho H, Salman H, et al. Natural fibre composites and their applications: a review. *J Compos Sci* 2018; 2: 66.
2. Dixit S, Goel R, Dubey A, et al. Natural Fibre Reinforced Polymer Composite Materials-A Review. *Polym Renew Resour* 2017; 8(2): 71–78.
3. Khan M, Rahamathbaba S, Mateen MA, et al. Effect of NaOH treatment on mechanical strength of banana/epoxy laminates. *Polym Renew* 2019; 10: 19–26.
4. Michael DP, Harish S, Bensely A, et al. Insulation characteristics of sisal, human hair, coir, banana fiber composites polymers from renewable resources *Polym Renew* 2010: 7
5. Rohit K and Dixit S. A review-future aspect of natural fiber reinforced composite. *Polym Renew Resour* 2016; 7(2): 43–59.
6. George SC, Jose T and Thomas S. Mechanical properties of short sisal fibre reinforced phenol formaldehyde eco-friendly composites. *Polym Renew* 2017 8
7. De Souza NCR and D'almeida JRM. Tensile, thermal, morphological and structural characteristics of abaca (Musa textiles) fibers, *Polym Renew* 5 2014.
8. Lefeuvre A, Garnier S, Jacquemin L, et al. Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050. *Resour Conserv Recycl* 2017; 125: 264–272.
9. Arjmand F, Barmar M and Barikani M. Isocyanate modification of wood fiber in enhancing the performance of its composites with high density polyethylene. *Polym Renew Resour* 2012; 3(2): 43–60.
10. Oromiehie A and Faghihi J. Physical-mechanical properties of polypropylene filled with wood fibre, Rice-Husk. *Polym Renew Resour* 2010; 1(2): 105–122.
11. Verma D and Senal I. Natural fiber-reinforced polymer composites. In: *Biomass, Biopolymer-Based Materials, and Bioenergy*. Amsterdam, Netherlands: Elsevier, 2019.
12. Keya KN, Kona NA, Kona FA, et al. Natural fiber reinforced polymer composites: history, types, advantages, and applications. *Mater Eng Res* 2019; 1: 69–87.
13. Ganvit VM and Sharma RK. Recent developments of Madhuca indica (Mahua) oil-based polymers: a mini review. *Polym Renew* 2022; 13: 55–70.
14. Gholampour A and Ozbakkaloglu T. A review of natural fiber composites: properties, modification and processing techniques, characterization, applications. *Journal of Materials Science* 2020; 55: 829–892.
15. Du X, Li Q, Wu G, et al. Multifunctional micro/nanoscale fibers based on microfluidic spinning technology. *Advanced Materials* 2019; 31: 1903733.
16. Haslinger S, Hummel M, Anghelescu-Hakala A, et al. Upcycling of cotton polyester blended textile waste to new man-made cellulose fibers. *Waste Management* 2019; 97: 88–96.

17. Royer S-J, Wiggin K, Kogler M, et al. Degradation of synthetic and wood-based cellulose fabrics in the marine environment: Comparative assessment of field, aquarium, and bioreactor experiments. *Science of The Total Environment* 2021; 791: 148060.
18. Rashid K, Haq EU, Kamran MS, et al. Experimental and finite element analysis on thermal conductivity of burnt clay bricks reinforced with fibers. *Constr and Build Mater* 2019; 221: 190–199.
19. Ramli N, Mazlan N, Ando Y, et al. Natural fiber for green technology in automotive industry: a brief review. *IOP Conference Series: Materials Science and Engineering* 2018; 368: 012012.
20. Mahmud S, Hasan KMF, JahidJahid MA, et al. Comprehensive review on plant fiber-reinforced polymeric biocomposites. *J of Mater Sci* 2021; 56: 7231–7264.
21. Preethikaharshini J, Naresh K, Rajeshkumar G, et al. Review of advanced techniques for manufacturing biocomposites: non-destructive evaluation and artificial intelligence-assisted modeling. *J of Mater Sci* 2022; 57: 16091–16146.
22. Radoor S, Karayil J, Rangappa SM, et al. A review on the extraction of pineapple, sisal and abaca fibers and their use as reinforcement in polymer matrix. *Express Polymer Letters* 2020; 14: 309–335.
23. A MK and S R. A review on natural fiber and its characteristics. *Industrial Engineering Journal* 2020; 13. DOI: 10.26488/iej.13.3.1224
24. Chokshi S, Parmar V, Gohil P, et al. Chemical composition and mechanical properties of natural fibers. *J Nat Fibers* 2020; 19: 3942–3953.
25. James DJames D JD, Manoharan S, Saikrishnan G, et al. Influence of bagasse/sisal fibre stacking sequence on the mechanical characteristics of hybrid-epoxy composites. *J of Nat Fibers* 2020; 17: 1497–1507.
26. Akampumuza O, Wambua PM, Ahmed A, et al. Review of the applications of biocomposites in the automotive industry. *Polym Compos* 2017; 38: 2553–2569.
27. Naik V, Kumar M, Kumar V, et al. A review on natural fiber composite material in automotive applications. *Eng Sci* 2021. DOI: 10.30919/es8d589
28. Zainal Abidin MR and Jamian S. Short review: crashworthiness characteristic of natural fiber composite. *International Journal of Management and Appl Sci* 2015; 1: 35–41.
29. Benin SR, Kannan S, Bright RJ, et al. A review on mechanical characterization of polymer matrix composites and its effects reinforced with various natural fibres. *Mater Today: Proc* 2020; 33: 798–805.
30. Patel N and Jain P. An investigation on mechanical properties in randomly oriented short natural fiber reinforced composites. *Mater Today: Proc* 2021; 37: 469–479.
31. Mongioví C, Morin-Crini N, Lacalamita D, et al. Biosorbents from plant fibers of hemp and flax for metal removal: Comparison of their biosorption properties *Molecules*. 26, 2021, p. 4199. DOI: 10.3390/molecules26144199
32. Sai Shravan Kumar P and Viswanath Allamraju K. A review of natural fiber composites [Jute, Sisal, Kenaf]. *Mater Today: Proce* 2019; 18: 2556–2562.
33. Silva WdM, Cesarino I, Rosa DdS, et al. Evaluation of phormium cookianum fibers as reinforcements for polypropylene-based composites. *J of Natur Fib* 2020; 17: 1039–1047.
34. Saba N, Tahir P and Jawaid M. A review on potentiality of nano filler/natural fiber filled polymer hybrid composites. *Polymers* 2014; 6: 2247–2273.
35. Shekar HSS and Ramachandra M. Green composites: a review. *Mater Today: Proc* 2018; 5: 2518–2526.
36. Tanasă F, Zănoagă M, Teacă C, et al. Modified hemp fibers intended for fiber-reinforced polymer composites used in structural applications—a review. I. Methods of modification. *Polym Compos* 2020; 41: 5–31.
37. Stawski D, Çalişkan E, Yilmaz N, et al. Thermal and mechanical characteristics of okra (*Abelmoschus esculentus*) fibers obtained via water- and dew-retting. *Appl Sci* 2020; 10: 5113.
38. Alvarado JJ, Chacón-Monge JL, Azofeifa-Solano JC, et al. Diversity of deep-sea echinoderms from Costa Rica. *Front in Mar Sci* 2022; 9. DOI: 10.3389/fmars.2022.918878

39. Karimah A, Ridho MR, Munawar SS, et al. A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations. *J of Mater Res and Technol* 2021; 13: 2442–2458.
40. Lan J and Qin G. The regulation of CIN-like TCP transcription factors. *Int J Mol Sci* 2020; 21: 4498.
41. Liu J and Lv C. Durability of cellulosic-fiber-reinforced geopolymers: a review. *Molecules* 2022; 27: 796.
42. Hughes M. Defects in natural fibres: their origin, characteristics and implications for natural fibre-reinforced composites. *J of Mater Sci* 2012; 47: 599–609.
43. Sadrmanesh V and Chen Y. Bast fibres: structure, processing, properties, and applications. *Int Mater Rev* 2019; 64: 381–406.
44. Musacchi S, Iglesias I and Neri D. Training systems and sustainable orchard management for european pear (*Pyrus communis* L.) in the mediterranean area: a review. *Agronomy* 2021; 11: 1765.
45. Singh RP, Prasad PVV, Sunita K, et al. Influence of high temperature and breeding for heat tolerance in cotton: a review. *Adv Agron* 2007, pp. 313–385.
46. Senthil C, Park JW, Shaji N, et al. Biomass seaweed-derived nitrogen self-doped porous carbon anodes for sodium-ion batteries: Insights into the structure and electrochemical activity. *J Energy Chem* 2022; 64: 286–295.
47. Tchicaillat-Landou M, Petit J, Gaiani C, et al. Ethnobotanical study of medicinal plants used by traditional healers for the treatment of oxidative stress-related diseases in the Congo Basin. *J Herb Med* 2018; 13: 76–90.
48. Tanasă F, Zănoagă M, Teacă CA, et al. Modified hemp fibers intended for fiber-reinforced polymer composites used in structural applications—A review. I. Methods of modification. *Polym Compos* 2020; 41(1): 5–31.
49. Lahsmin YK, Tahir D, Abdullah B, et al. Synthesis of carbon nanosphere at low temperatures based on bamboo fiber. *Mater Sci Forum* 2019; 966: 163–168.
50. Narayanasamy P, Balasundar P, Senthil S, et al. Characterization of a novel natural cellulosic fiber from Calotropis gigantea fruit bunch for ecofriendly polymer composites. *Inter J of Biological Macromolecules* 2020; 150: 793–801.
51. Nofal RM. *Biodegradable Textiles, Recycling And Sustainability Achievement*. Berlin: Springer 2022. DOI: 10.1007/978-3-030-83783-9
52. Nurazzi NM, Asyraf MRM, Rayung M, et al. Thermogravimetric analysis properties of cellulosic natural fiber polymer composites: a review on influence of chemical treatments. *Polymers* 13, 2021, p. 2710
53. Yang T, Zheng TH, Zhao Q, et al. Sound absorption properties of natural fibers: a review. *Pharm Biol* 2020; 58: 1–7.
54. Bakar N, Chin SC, Siregar JP, et al. A review on physical, mechanical, thermal properties and chemical composition of plant fibers. *IOP Conf Ser: Mater Sci Eng*. 2020; 736: 052017.
55. ShuvoShuvo II. Fibre attributes and mapping the cultivar influence of different industrial cellulosic crops (cotton, hemp, flax, and canola) on textile properties. *BioresourBioprocess* 2020; 7: 28–51.
56. Sanivada UK, Mármol G, Brito FP, et al. PLA composites reinforced with flax and jute fibers-a review of recent trends, processing parameters and mechanical properties. *Polymers* 2020; 12: 2373–2429.
57. Shah SS, Shaikh MN, Khan MY, et al. Present status and future prospects of jute in nanotechnology: a review. *Chem Rec* 21: 2021, pp. 1631–1665. DOI: 10.1002/tcr.202100135
58. Islam MH, Islam MR, Dulal M, et al. The effect of surface treatments and graphene-based modifications on mechanical properties of natural jute fiber composites: a review. *iScience* 2022; 25: 103597.
59. Futalan CM, Choi AES, Soriano HGO, et al. Modification strategies of kapok fiber composites and its application in the adsorption of heavy metal ions and dyes from aqueous solutions: a systematic review. *Int J Environ Health Res* 2022; 19: 2703. DOI: 10.3390/ijerph19052703
60. Hashemifard H, Mehranzadeh M and Chenari M. Mechanical and physical properties of Sugarloaf. *Adv Environ Biol* 2012; 6: 368–375.

61. Cesarino I, Roberta G, Bronzato F, et al. *Pineapple leaf fibers*, Berlin: Springer 2020. DOI: 10.1007/978-981-15-1416-6
62. Ramesh M. Flax (*Linum usitatissimum* L.) fibre reinforced polymer composite materials: a review on preparation, properties and prospects. *Prog Mater Sci* 2019; 102: 109–166.
63. Toumpanaki E, Shah DU and Eichhorn SJ. Beyond what meets the eye: imaging and imagining wood mechanical-structural properties. *Adv Mater (Deerfield Beach, Fla.)* 2021; 33: e2001613–e2001622.
64. Gao X, Zhu D, Fan S, et al. Structural and mechanical properties of bamboo fiber bundle and fiber/bundle reinforced composites: a review. *J Mater Res* 2022; 19: 1162–1190.
65. Li M, Pu Y, Thomas VM, et al. Recent advancements of plant-based natural fiber-reinforced composites and their applications, *Compos B Eng* 2020; 200: 108254. DOI: 10.1016/j.compositesb.2020.108254
66. Aaliya B, Sunooj KV and Lackner M. Biopolymer composites: a review. *Int J Biobased Plast* 2021; 3: 40–84.
67. Uppal N, Pappu A, Gowri VKS, et al. Cellulosic fibres-based epoxy composites: from bioresources to a circular economy. *Ind Crops Prod* 2022; 182: 114895.
68. Marvila MT, Rocha HA, de Azevedo ARG, et al. Use of natural vegetable fibers in cementitious composites: concepts and applications. *Innov Infrastruct Solut* 2021; 6: 180–224.
69. Jeyabalaji V, Kannan GR, Ganeshan P, et al. Extraction and characterization studies of cellulose derived from the roots of *Acalypha indica* L. *J Nat Fibers* 2021; 19: 1–13.
70. Gao Y, Mohammadifar M and Choi S From microbial fuel cells to biobatteries: moving toward on-demand micropower generation for small-scale single-use applications. *Adv Mater Technol* 2019; 4: 1900079.
71. Awais H, Nawab Y, Amjad A, et al. Environmental benign natural fibre reinforced thermoplastic composites: a review. *Composites Part C: Open Access* 2021; 4: 100082.
72. Veerasimman A, Shanmugam V, Rajendran S, et al. Thermal properties of natural fiber sisal based hybrid composites—a brief review. *Journal of Natural Fibers* 2022; 19: 4696–4706.
73. Hosseinali F and Thomasson J Multiscale frictional properties of cotton fibers: a review. *Fibers* 2018; 6: 49.
74. Ahmad J, Majdi A, Deifalla AF, et al. Concrete reinforced with sisal fibers (SSF): overview of mechanical and physical properties. *Crystals* 2022; 12: 952.
75. Zhu J, Zhu H, Njuguna J, et al. Recent development of flax fibres and their reinforced composites based on different polymeric matrices. *Materials* 2013; 6: 5171–5198.
76. Liu M, ThygesenGao M, SummerscalesLi CZ, et al. Targeted pre-treatment of hemp bast fibres for optimal performance in biocomposite materials: a review. *Ind Crops Prod* 2017; 108: 660–683.
77. Hassan F, Zulkifli R, Ghazali MJ, et al. Kenaf fiber composite in automotive industry: an overview. *Int J Adv Sci Eng Inf Technol* 2017; 7: 315–321.
78. Kiruthika AV. A review on physico-mechanical properties of bast fibre reinforced polymer composites. *J Build Eng* 2017; 9: 91–99.
79. Jain A, Rastogi D and Chanana B. Bast and leaf fibres: a comprehensive review. *Int J Home Sci* 2016; 2: 313–317.
80. Jeyapragash R, Srinivasan V and Sathiyamurthy S. Mechanical properties of natural fiber/particulate reinforced epoxy composites - a review of the literature. *Mater Today: Proc* 2020; 22: 1223–1227.
81. Mwaikambo LY and Mwaikambo LY. Review of the history, properties and application of plant fibres investigation of the performance of cotton woven fabrics view project review of the history, properties and application of plant fibres, 2006, https://www.researchgate.net/publication/284760719
82. Ibrahim ID, Jamiru T, Sadiku ER, et al. Mechanical properties of sisal fibre-reinforced polymer composites: a review. *Compos Interfaces* 2016; 23: 15–36.
83. Salema AA. Potentials materials for food packaging from nanoclay antural fibers filled composites Related papers. *Mater Des* 2012; 46: 391–410.

84. Senthilkumar K, Saba N, Rajini N, et al. Mechanical properties evaluation of sisal fibre reinforced polymer composites: a review. *Constr Build Mater* 2018; 174: 713–729.
85. Monteiro SN, Calado V, Rodriguez RJS, et al. Thermogravimetric stability of polymer composites reinforced with less common lignocellulosic fibers—an overview. *J Mater Res* 2012; 1: 117–126.
86. Zheng Y, Wang J, Zhu Y, et al. Research and application of kapok fiber as an absorbing material: a mini review. *J Environ Sci* 2015; 27: 21–32.
87. Bouzouita A, Notta-Cuvier D, Raquez J-M, et al. Poly(lactic acid)-based materials for automotive applications, *Industrial Applications of Poly(lactic Acid)* 2017, pp. 177–219.
88. Blanco Parte FG, Santoso SP, Chou CC, et al. Current progress on the production, modification, and applications of bacterial cellulose. *Crit Rev Biotechnol* 2020; 40: 397–414.
89. Elseify LA, Midani M, El-Badawy AA, et al. Comparative study of long date palm (*Phoenix dactylifera* L.) midrib and spadix fibers with other commercial leaf fibers. *Cellul* 2023; 30: 1927–1942.
90. Fang Z, Li B, Liu Y, et al. Critical role of degree of polymerization of cellulose in super-strong nanocellulose films. *Matter* 2020; 2: 1000–1014.
91. Berglund J, Mikkelsen D, Flanagan BM, et al. Wood hemicelluloses exert distinct biomechanical contributions to cellulose fibrillar networks. *Nat Commun* 2020; 11: 4692.
92. Shiga TM, Yang H, Penning BW, et al. A TEMPO-catalyzed oxidation-reduction method to probe surface and anhydrous crystalline-core domains of cellulose microfibril bundles. *Cellul* 2021; 28: 5305–5319.
93. Shi J, Liu X, Xia C, et al. Visualization of wood cell structure during cellulose purification via high resolution X-ray CT and spectroscopy. *Ind Crops Prod* 2022; 189: 115869.
94. Nuez L, Magueresse A, Lu P, et al. Flax xylem as composite material reinforcement: microstructure and mechanical properties. *Compos A: Appl Sci Manuf* 2021; 149: 106550.
95. Chen C, Kuang Y, Zhu S, et al. Structure-property-function relationships of natural and engineered wood. *Nat Rev Mater.* 2020; 5: 642–666.