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Review Article

A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations

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ABSTRACT

Understanding the basic properties of natural fibers is important to determine the optimal intended uses for instance as high-quality bio-composite raw material. This review describes the characteristics, and potential uses of some natural fibers in order to improve their sustainability and economic values. The natural fibers have low density and high strength to weight ratio and reduction make them potential as light weight composite and reinforcement materials. The microstructure and chemical compositions of fibers affect the mechanical properties with the fiber cross-sectional area is the most variable influencing the fiber strength. Natural fibers are easy to absorb water due to the presence of hemicellulose that give hydrophilic properties make them less compatible in the interaction with matrix with hydrophobicity properties. Higher cellulose content and crystallinity tend to result better strength properties of fiber while lignin is since versa. Besides that, fiber anatomical characteristics vary between different and same species that affect on the density and mechanical properties. The other factors namely environmental conditions, method of transportation, storage time and conditions, and fiber extraction affect the size and quality of the natural fibers.

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1. Introduction

Today, scientists around the world are concerned to the protection of the atmosphere and the biodiversity, by enhancing the sustainability and quality of eco-friendly products. Due to the bio-renewable properties and eco-friendly behaviors, people return to natural fibers to replace synthetic and hazardous materials. Some disadvantages of natural fiber, such as biocompatibility and hydrophilic properties, can be overcome by several surface modifications and methods of treatment of chemicals to achieve sufficient uses. They have been used successfully for many purposes, such as composite materials-despite their lower density compared to glass fiber construction and engineering fields, textile, biomedical, biopolymer, biosensors, and smart packaging. The utilization of natural fibers would help to mitigate pollution issues, such as waste, landfill, toxic, and greenhouse gases emissions [1–3].

Fiber is a type of material that is intact, long, thin, and simple to bend to form an elongated tissue [4]. According to the sources of the materials, fibers are categorized into three groups, namely natural, semisynthetic, and synthetic sources. Natural fiber is abundant and more affordable in comparison with synthetic fiber specifically lower density and energy requirements, renewability, no skin irritation, higher strength-to-weight ratio, higher aspect ratio length to diameter (L/D) of around 100, and higher strength and elasticity modulus, showing great potential as glass, carbon, or other synthetic fiber replacements. In addition, these benefits have led to the use of natural fiber for human needs as well as for industrial raw materials such as textiles, pulp and paper, accessories, bio-composites, and crafts [5]. Natural fibers remain in demand and compete for consistency, longevity, colour, and shine with wool, silk, and synthetic fibers.

Natural fiber consists of plant, mineral fibers, and animal. Protein and cellulose, respectively, are the principal components of animal and plant fibers. Furthermore, the fiber plant is divided into stems, leaf, seed, xylem, bark, and fruit. These fibers come from primary or secondary meristematic tissue depending on the species. Rice, bamboo, corn stem, wheat, and bagasse are also included in the stem fiber. The examples of fruit fibers include oil palm andcoconut, while leaf fibers include abaca, pineapple, sisal, and agave. Furthermore, examples of seed fibers include wider, kapok, and cotton. Bark fibers are rosella, jute, hibiscus, abaca, soybean fiber, ramie, while animal fibers include wool, silk, bird fiber, hair, and collagen fibers. Asbestos, carbon, and glass are examples of mineral fibers [6–10].

Indonesia and Malaysia have a high potential for bio-resources that have not been optimally studied and fiber is one of them. From 2013 to 2015, Indonesia's cotton, ramie, abaca and pineapple production reached 1,200, 1023, 6,8 million, and 1,8 million tons per year [11]. Malaysia, like Indonesia, has a high natural fiber potency. Every month, the 'Panasonic Electric Works Kenaf' in Malaysia uses roughly 600 tonnes of kenaf fibre to make fibre board [12]. The world's pineapple plantation area reached roughly 1,022,319 ha in 2014, according to data from the Malaysian Pineapple Industry Board (MPIB), producing 25, 439, 366 MT of pineapple. Furthermore, Malaysia has a plenty of pineapple raw material waste to meet the needs of composite manufacturers and research and development departments [13]. Malaysia's most cost-effective oil crop is oil palm. With 352,385 ha of plantation, Malaysia became the world's biggest producer and exporter of palm oil in 1971. The overall cultivated area increased by 3.87 million hectares in 2004. Oil palm development will generate a substantial amount of waste, estimated to be over 30 million tons of oil palm biomass per year, comprising trunks, fronds, and empty fruit bunches that can be utilized as useful fibers [14].

Malaysian natural fibers have enormous potential in a variety of fields. Many studies on the usage of fiber, such as the usage of Malaysian Yankee Pineapple AC6 leaf fiber treated with silane in composites for diverse industrial uses, have been undertaken [13]. Automotive manufacturers have employed kenaf, flax, abaca, and hemp for door panels, seat backs, various interior trim, and spare-wheel pans in particular. Jute-based composites, such as jute thermoplastic board, are created from jute and plastic waste and can be used to make sheet/boards, doors, furniture, window frames, fences, and other items, may be considered as new application for future development [12].

On the basis of this availability, technical viability makes natural fiber an attractive replacement for unsustainable glass and carbon fiber reinforced composites as an attractive bio-resource for raw materials [15]. Scientists are concerned with eco-friendliness and sustainability in designing new bio-products [15–17]. However, environmental impact assessment (EIA) and life cycle assessment (LCA) should also be accessible for the future in the production of new products due to the conservation of resource demand [18]. The LCA is a method for evaluating the effects of goods or services, while the EIA is an interrelated process that helps to determine the influence of products and services on the environment [19]. This paper reviews studies from 1995 to 2020 and describes the characteristics (physical, mechanical, chemical and anatomical), and potential use of some natural fibers mainly for eco-friendly bio-composites in order to improve their sustainability and economic values.

2. Types of natural fibers and their utilization

Botanical types are the most common classification for natural fibers. According to [20], five specific types of natural fibers are categorized by this approach, namely (i) bast fibers such as jute, flax, cannabis, ramie and kenaf, (ii) leaf fibers such as banana, sisal, agave, and pineapple, (iii) seed fibers such as coir, cotton, and kapok, (iv) grass and reeds such as wheat, maize, and rice, (v) all other types such as roots and wood. There are some crops that produce more than one type of fiber. For instance, both bast and core fibers have jute, flax, hemp and kenaf, while agave, coconut and oil palm have both fruit and stem fibers. Cereal grains, in addition, have both stem and hull fibers [21].

Recently, Suparno [5] reported potential and future efforts of Indonesia's natural fiber as raw material for various industries, and summarized in Table 1. Table 1 shows the types and use of natural fibers that have been documented of

Table 1 – Types of natural fiber and their utilization.

Types of natural fibers	Utilizations	Latest references
Abaca	Textiles, clothes, and useful papers such as money, journal, and check paper, as well as composites	[22]
Bamboo	Lactic acid, construction, vinegar, charcoal, methane, composite reinforcement, shoes, food, textiles, pulp and paper production, shocks, and bioenergy sources.	[23]
Banana/Musa	Rope, place mats, paper cardboard, string yarn, tea bags, high-quality textile/fabric fabrics, currency note paper, mushroom, art/handicraft, cordage, cushion cover, table cloth, curtain, natural absorbent in colored wastewater, oil absorber, light weight composites, and bio-fertilizer.	[24,25]
Biduri	Heat insulation material	[26]
Coir	Filler, reinforcement in composite materials, light weight composites	[5,24]
Collagen fiber	Tissue manipulation, operating sewing thread	[5]
Cotton	Fabric, clothes, yarn, furniture industry as coating materials	[22]
Derris scanden	Reinforcing agent alternatives for synthetic fibers in polymer matrix composite	[27]
Hemp	Bags, tarpaulins, carpets, rope, furniture materials, fabric, textile, garden mulch, fleeces and needle felts, light weight composites, composites, geotextiles/geotextile insulation industry	[3]
Jute	Bags, sack, carpets, carpet upholstery, transportation or geotextile, electrical insulation and ropes, tarpaulins, packaging, furniture materials, fabric, light weight composites	[5]
Pineapple	Bags, table linens, mats, ropes, pulping material, handbags, composites, lightweight duck cloth, conveyor belt cord, coasters and many other interior design products, and livestock and agriculture	[28]
Kenaf	Pulp and paper product	[5]
Ramie	Textile, paper, pulp, yarn, biofuel, fabric, oil, resin, wax, seed food, composites, livestock, and agriculture,	[5]
Silk	Silk cloth, silk yarn	[5]
Wool	Cotillion, wool yarn	[5]
Sorghum bagasse	Particle board, sugar production sources, pulp, and paper	[29–32]

various studies in latest references. Usage of composites based on natural fiber in automotive interior linings (roof, side panel lining, rear wall, furniture, building, packaging, and pallets for shipping have also reported by Kumar and Hiremath [33], Sood and Dwivedi [34], and Lau et al. [35],

The presence of hydroxyl and other polar groups, dead cells, wax and oil, and low fire resistance makes natural fibers in raw conditions not compatible with polymers and causes the formation of aggregates. Furthermore, the high water absorption of natural fiber causes low interface strength than glass or carbon fibre composites. For developing eco-friendly composite applications, basic properties and components of natural fibers need to be properly understood. Furthermore, in order to utilize natural fiber as textiles, some properties such as length, flexibility, and strength need to be fulfilled. The most important properties considered in substitution of synthetic fibers are fiber ratio of length and width. Natural fiber yarns or synthetic fibers consist of short (staple) or very long fibers (filament) and are intended to provide a flexible and easily concatenated yarn [36]. Generally, the natural fibers are present in the form of staples with few inches in length excluding silk fibers [36], and could be mixed with semi-synthetic (semi-cellulose, protein or mineral) or synthetic fibers. Viscose and acetate rayons, and kupri ammonium are semi-synthetic fiber. While synthetic fibers are produced by condensation (nylon, polyester and spandex) and addition of polymers such as acrylate [36].

Dhaliwal [22] stated that stretching, calendaring and production of hybrid yarns are modifications that could be used the change physical characteristics of natural fibers. Furthermore, Sudjindro [37] stated that abaca fibers have high potency to be used as raw materials in textile industries because they are strong, resistant to humidity, and have salty water. Biduri fibers have a hollow shape that functions as a medium/air trap in order to control the flow of heat flow [38]. They could be used as a natural, renewable and environmentally friendly heat insulation materials. Biduri fiber does not cause allergies, and are mild and hydrophobic [26].

Munawar et al. [39] stated that ramie bast fiber, pineapple and sansevieria leaves are prospective high-performance plant fiber composites based on their high mechanical properties. Kandachar and Bruwer [40] also reported that because of its high strength and stiffness, this hemp fiber is also used as reinforcement biocomposites. Composite materials of natural fibers have great potentials, especially in the automotive industry. They are generally used in interior parts such as door panels, dashboard parts, parcel shelves, seat cushions, backrests and cable linings [41–43]. Pineapple fibers, copolymer and composites in automobiles and railway coaches [28,44] are used in textile industries because they have a very high initial modulus [44].

Water retting method is used to extract fiber from natural sources such as the *Sansevieria trifasciata* plant. The results showed that the fiber had good strength and fineness with low elongation. Due to its greater strength, cost-effective and renewable source, it could be used to make products like sacks, ropes, handicrafts, mattresses for bedding and other wider applications of textiles [45]. Furthermore, sisal fibers are used as polypropylene reinforcement for good application [46]. The extraction of fibers from *Derris scanden* stem were carried out by Ilaiya Perumal and Sarala [27]. Based on their properties, these fibers may become promising candidates for reinforcing agent and alternatives for synthetic fibers in polymer matrix composite, thereby creating an economic value for the plant and providing benefits to the society and environment.

Fig. 1 shows the potential application of banana pseudo-stem component which is divided into three parts, namely central core, banana fiber and waste materials after fiber extraction. While prospective utilization of pineapple leaf is presented in Fig. 2. Some utilizations of banana fibers have been reported including in papermaking [48,49], fiber-cement composites [50–52], animal feed due to high cellulose and starch content [53], fiber-polymer composites [25,47,54], binder less fiberboard [55], rope, place mats, paper cardboard, string thread, tea bags, high-quality textile/fabric materials, currency note paper, mushroom, art/handicraft, cordage [47,56], cushion cover, table cloth, curtain [57]. These fibers are also used as natural absorbent in colored wastewater from dyes of textile industries and an absorbent for oil spillage in refineries [58,59]. Furthermore, banana pseudo-stem has antimicrobial properties [58], and could be used as bio-fertilizers [60].

3. The physical–chemical properties of natural fibers

This section presents the studies on physical, and mechanical properties of natural fibers. Furthermore, the physical, chemical and morphological properties influence the

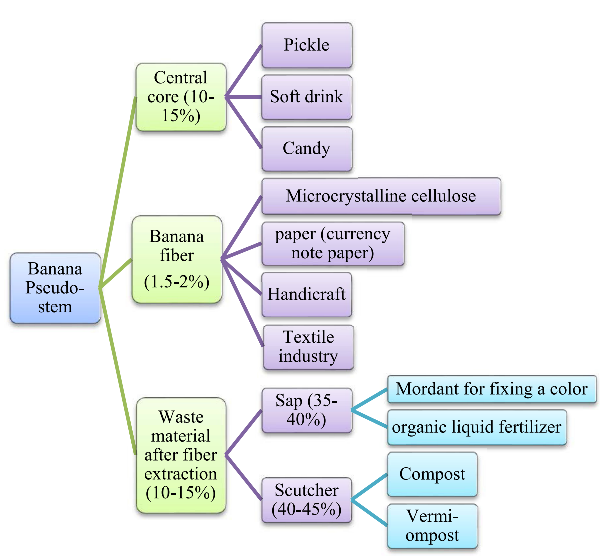

Fig. 1 – Potential application of banana pseudo-stem component [47].

mechanical properties of plant fibers [61]. While the shape, size, crystallite content, orientation, and thickness of the cell walls influence the properties of a single fiber [62]. Generally, natural fibers have characteristics such as low energy consumption, low density, non-abrasive nature, low cost, renewability, biodegradability, easy availability, and worldwide abundance [63].

The size and quality of fibers are affected by environmental conditions such as the growth, location such as altitude or place, nutrient, temperatures and season, and local climatic condition [64–66]. Moreover, the harvest phase, thickness and adhesion between these fibers also affects their qualities. The supply phase which include method of transportation, storage time and conditions also contributes to their qualities [64,65]. In addition, the part of the plant in which these fibers are extracted from also contributes to the difference in their properties [66], therefore in order to obtain optimum fiber qualities, all the above factors need to be optimized.

The most popular natural fibers in Indonesia are kapok, ramie, pineapple, sansevieria, kenaf, abaca, sisal, and coconut fiber [39]. Flax and hemp are two natural fibers that have high mechanical strength [67]. Furthermore, the ultimate tensile strength of bamboo is relatively higher than most of other fiber plants, such as jowar and sisal [68]. The evaluation of fiber strength is carried out using a single unit fiber or fiber-bundle tests. Even though the exact results are provided in the test of a single unit fiber, in practical use, the fiber-bundle test is more accepted because it is easily carried out and produce faster results [39]. Furthermore, Munawar et al. [39] stated that the main variable influencing fiber strength is the fiber cross-sectional area. And the mechanical properties of fibers are influenced by their microstructure and chemical composition [69]. In addition, the presence of cellulose, hemicellulose, and lignin of natural fibers, extraction method and chemical treatment affects the tensile strength. While alkali soaking of *Parthenium Hysterophorus* increases the tensile strength value [70].

Cellulose correlated positively with tensile strength and Young's modulus, while lignin affected since and vice versa. Besides cellulose, hemicellulose and wax contents has positive correlation with Young's modulus. Furthermore, lignin and pectin contents reduced the specific Young's modulus, while moisture gain was affected by hemicellulose and lignin. The relationship between the chemical composition, and mechanical and physical properties of fiber is shown in Table 2 [71].

Natural fibers have lower tensile strength compared to synthetic fibers, however, they offer more advantages compared to synthetic fiber. Furthermore, they are usually rigid, not fractured during processing and have comparable specific strength and stiffness to glass fibers [72]. They have lower density and competitive Young's modulus or elasticity [73]. Some of them have high density, tensile strength, stiffness and strain. The properties comparison between natural fiber and synthetic fiber resume by Asim et al. [44]. Natural fiber was lower density, cost, energy consumption, than synthetic fiber/glass fiber. Naturally, natural fibers were renewability, recyclability, and CO_2 neutral while glass fiber was since versa. Both natural fiber and glass fiber have wide distribution. Glass fibers have abrasion to the machine and

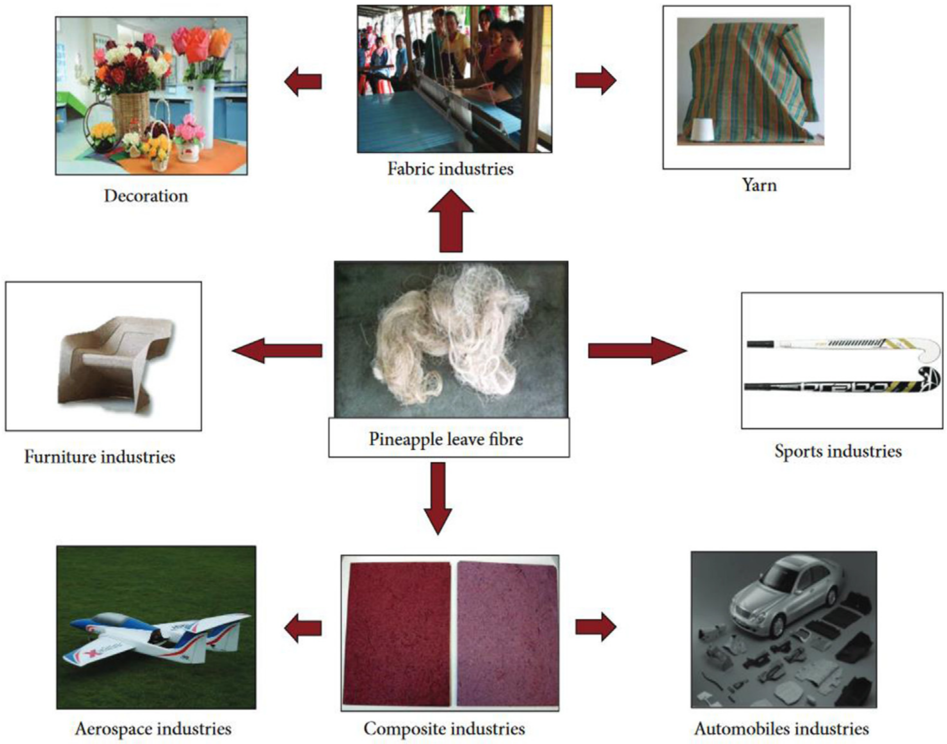

Fig. 2 – Various present and applications of pineapple leaves [44].

health risk when inhaled, while natural fiber does not these properties. From point of view the disposal, natural fiber can be degraded, while glass fiber includes in non-biodegradable properties.

The porous nature of fibers is a major problem in obtaining the reliable value of its density. Ramie bast and sisal leaf fibers have high (1.38 g/cm^3) and low densities (0.76 g/cm^3) [39]. While that of natural fibers (1.2–1.6 g/cm^3) are lower than glass fiber (2.4 g/cm^3), therefore this leads to the production of light-weight composites [3]. The increase in the porosity of fiber is directly proportional to the lumen size and density and vice versa [39]. Table 3 shows the increase of fiber bundle diameter because of the decrease in density.

To ensure the proper use of natural fiber, it is important to understand its basic physical–mechanical properties. Furthermore, in order to determine the interaction between their weight and the increase in tensile strength, a specific quantity need to be used. Table 3 shows the specific tensile strength values of natural fibers after being compared with the density of each fiber. Abaca is a type of natural fiber that has the highest specific strength and light weight. Table 3 also shows that the specific toughness of natural fibers, in banana, jute, hemp and pineapple fibers have high values. The value of the specific tensile strength and specific stiffness possessed by natural fibers indicates that they are suitable for use as reinforcing materials in composites. According to Ashik et al. [87], natural fibers such as sisal and jute fiber could be used to replace the glass and carbon fibers due to their easy availability and low cost. Natural fibres include flax, hemp, jute, sisal, kenaf, coir and many others are inexpensive, abundant and renewable, lightweight, with low density, high toughness. Furthermore, they are biodegradable and have the potency of being used as a replacement for traditional reinforcement materials in composites for applications which require high strength to weight ratio and reduction [85].

Table 2 – The influence of chemical composition on the mechanical–physical properties of natural fiber.

Chemical component of natural fibers	Parameters of mechanical properties				Parameters of physical properties		
	Tensile strength	Specific Young's Modulus	Failure strain	Microfibril Angle (MFA)	Diameter	Density	Moisture Gain
Cellulose	xxx	xx	–	–	x	xxx	–
Hemicellulose	–	xxx	xx	–	x	–	Xx
Lignin	–	–	xxx	xxx	–	–	Xx
Pectin	–	–	xx	xxx	–	xxx	–
Wax	–	xx	–	–	–	–	X

Note: Symbol:(x): positive correlation, (–): negative correlation.

Table 3 – The physical-mechanical characteristic of natural fiber.

Type of fiber	Average Diameter of fiber (μm)	Density (g/cm^3)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation (%)	Specific Tensile strength (MPa)	Specific modulus (GPa)	Toughness (MPa)
Abaca	122 [39]	0.83–1.3 [39,66]	650–780 [66]	29–32 [66]	2–4 [66]	500–939[a]	15.6 [39]	21.5 [39]
Acacia tortilis	–	0.906 [74]	71.63 [74]	4.2 [74]	1.328 [74]	79.06[a]	4.64[a]	–
Softwood (kraft pulp)	–	1.5 [75]	1000 [75]	40 [75]	4.4 [75]	–	–	–
Bamboo	–	0.91 [76]	262 [77]	9.8 [77]	2.7 [77]	297.9[a]	10.77[a]	–
Banana	80–250 [47]	1.3 [78]–1.35 [47,76] 1.4 [79]	355–754 [47,76,78,79]	7.7–33.8 [47,78,80]	5.3 [78]	273–560.77[a]	25–26[a]	–
Coir/husk	121.3 [39], 100–450 [47]	0.87–1.2 [39,47,75,76]	95–593 [47,75,76]	4–6 [47,75,81], 6	4–47 [47,75,81]	158 [39]	4.2 [39]	10.7 [39]
Cotton	–	1.5–1.54 [75,76,79]	200–800 [75,76,79,81]	5.5–13 [80,81]	3–10 [44,75,81]	125–500[a], [82]	3.5–8.1 [82]	–
Jute	–	1.3–1.46 [75,76,79]	393–900 [44,75,76]	10–55 [44,75,80,81]	1.5–1.8 [75,81]	273.97–616.44[a]	6.85–38[a], [83]	–
Kenaf	68.5–300 [39,84]	1.31–1.5 [39,56,75,76,79]	930–1500 [75,76,79,84]	23–53 [56,75,79]	1.6–17.3 [56,75]	361–641 [39,82]	19.2–36.5 [39,82]	52 [39]
Pineapple	20–80 [39,44,47]	1.32–1.543 [39,44,47,85]	654,413–1627 [44,47]	34.5–82.51 [44,47]	0.8–27 [47,80,85]	300–1100 [39,44]	20.554.3 [39,83]	95 [39]
Ramie	49.6 [39]	1.38–1.6 [39,76,79]	400–1000 [75,76,79,81]	44–128 [75,76,80,81]	2–3.8 [75,81]	220–938[a] [39,44]	20.6 [39]	16 [39]
Sisal	50–200 [39,47]	0.76, –1.58 [39,47,66,75,76,79]	274–855 [66,75,76,81]	9–38 [47,66,75,80,81]	2–7 [47,66,75,81]	341–700 [39,44,82]	6.3–12.1 [39,82,83]	10 [39]
Flax	–	1.5 [75]	1500 [75]	27.6 [75]	3.2 [75]	–	–	–
Hemp	–	1.47 [75]	690 [75]	70 [75]	4 [75]	–	–	–

[a] Calculated by the equation in Brad Peirson [86].

The observation of Munawar et al. [39] on the stress–strain of natural fibers indicates that ramie, pineapple, sansevieria, kenaf and sisal had low strain (2–6%) and high stress, while *Cocos nucifera* husk fiber had high strain (24%) with low stress. The stress–strain curve of pineapple fiber had a similar trend to that of jute fibers [88]. A high performance of the mechanical properties of ramie bast fiber was influenced by high molecular weight (1000) and cellulose content (69–97%) with small spiral angle (7–12%) [89–93]. Sudjindro [37] stated that sisal fiber has high tensile strength, porosity, bulk, absorbency, and folding strength. While bast fibers have high tensile strength and stiffness, cheap, high performance, and easily available [62]. However, these fibers have low stiffness that is balanced by high elongation and elastic recovery [62]. Compared to the synthetic fibers, the pseudo-stem banana fiber has high mechanical strength. Furthermore, the incorporation of sisal/jute with glass fibers improved the tensile and flexural strength [94].

Animal fibers are durable with moderate resistance, poor conductors of heat, very sensitive to some alkali and able to provide reinforcement in multi-axial situation compared to natural fibers [62]. According to Hariprasad et al. [95] hay fiber increases the tensile capacity of polypropylene composite and milkweed fiber, kusha grass and sisal fiber and improve the tensile strength of polypropylene.

4. Chemical component

Generally, all plants contain cellulose, hemicellulose and lignin, which constitute the three major organic constituents of plant cell walls and these natural structural polymers are known as lignocellulose. In addition, natural fibers also contain pectin, waxes and water-soluble substances and oil [96–98]. There is a variation in the chemical composition of fibres even within the same plant species affected by the growth conditions of the plant, geographical factors and the method of fibre extraction [96].

The properties of fibers are affected in the microfibril angle and the arrangement inside the cell wall [99]. Though plants are composed of lignocellulosic material, substantial differences may be observed between diverse types of plant that have an impact on how different plant material may be used in the manufacturing process [100]. Fig. 3a and b shows the position of chemical components, while Table 4 showed the chemical properties of some natural fibers. The cellulose amount increases from primary layer (S1) to secondary layer (S2), while hemicellulose content remains the same in each layer, but lignin content is reciprocal with tendency of cellulose. Hemicellulose bonds with cellulose and together they make a network with lignin and pectin to provide the adhesive quality. While S2 is responsible to the physical and mechanical strength of fibres. Furthermore, better strength properties are achieved with high level of cellulose content and lower microfibrillar angle [126,127].

Based on Table 4, there are variation between the same species of natural fiber on the chemical component summarized from previous studies. It supports previous study that stated many factors influence the qualities and chemical component of natural fibers. They include the environmental

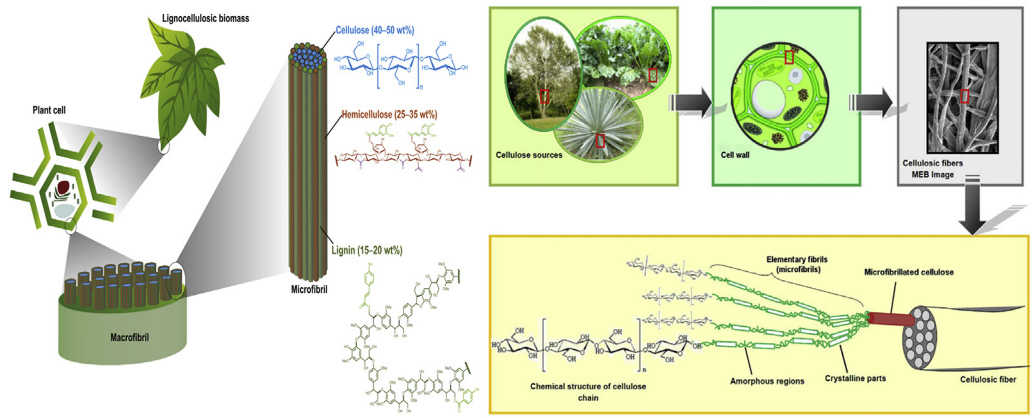

Fig. 3 – (a) Position of chemical component and fibers of biomass (Reprinted with permission from Elsevier, License Number: 5071091063061) [101], (b) From the cellulose sources to the cellulose molecules: details of the cellulose microfibrils (in color) (Reprinted with permission from Elsevier, License Number: 5071091475282) [102].

condition to growth, the extraction method, harvesting time, method to harvest the major component in natural fibers is cellulose. Furthermore, this indicates that plants give response to environmental condition and the positions of the extracted fiber. In order to maintain the quality of product developed from natural fiber, it is important to overcome variation of fiber qualities. Furthermore, by understanding these properties, it is important to choose the appropriate method in preparing these plants.

Natural fibers with relatively high cellulose content include cotton linter, cotton, ramie, and kapok. Basically, high cellulose content and the lowest lignin provide high tensile strength. However, the correlation is not always linear due to many factors that affects the tensile strength. Cellulose, especially the crystalline parts give great influence to the tensile strength value, because the higher the crystallinity of cellulose, the greater the fiber strength. The position of lignin on biomass also affects the tensile strength and makes it lower because lignin is between cellulose and hemicellulose, and become weaker.

The structure of cellulose [101], hemicellulose [101] and lignin [101] are presented in Fig. 3a. The cellulose content is based on the age and species of the plant. Cellulose is a hydrophilic glucan polymer with higher thermal stability than hemicellulose and is formed by a linear chain of glucose unit linked together through β (1 →4) bonds with high degree of polymerization. Cellulosic plant fibers have high moisture absorption capacity and poor dimensional stability because they usually swell in contact with water [128]. Adhesion between fibers and matrix with natural fibers as reinforcement could be affected by both the hydrophobicity and hydrophilicity of fibers and its interaction with the matrix [129]. The properties and degradability of natural fibers are influenced by different cell wall polymers of lignocellulosic materials [130]. In addition, cellulose gives effect on the strength of natural fibers, while lignin improves the UV degradation and char formation.

Hemicellulose is placed third position in the abundance of cell wall constituent of lignocellulosic biomass, and has branch structures with low degree of polymerization. Therefore, during the pretreatment of lignocellulose, this biopolymer is more degraded easily in liquid fraction. Pentose is the main hemicellulose in non-wood plants, therefore a larger amount influences the fibrillation of fibers and consequently increase the bonding potential of pulp sheets [131]. During the utilization of paper sheet, high hemicellulose content facilitates the flexibility of fiber, thereby making it easy for it to swell and high surface area obtained. The lesser the quantity of hemicellulose, the higher the crystallinity of cellulose. Therefore, low hemicellulose content gives positive effect on cellulose in amorphous zone [132].

Furthermore, Azwa et al., [130], stated that hemicelluloses are responsible to thermal, biological, moisture degradation and absorption in natural fibers [133]. A High content of hemicelluloses has positive correlation with moisture sorption and biodegradation. Furthermore, hollow cavities in natural fibers decrease the bulk density, results in light weight, and absorbs more water. While the moisture content of fibers affects the degree of crystallinity, orientation, tensile strength, swelling behaviour, and porosity of fibers. Therefore, the higher the moisture absorption, the greater the microbial attack [134].

The presence of –OH and –COOH groups on the structure of natural fibers enhance the fixation of reactive dyes [135]. While the alkali treatment (addition of NaOH) on natural fibers (*Pennisetum orientale grass*) removes excess amorphous content like lignin, pectin, hemicellulose, wax and cellulose. Therefore, the density and thermal stability of the NaOH that was treated with *P. orientale* fibers was higher compared to the treatment with HCl and untreated fibers [136].

Lignin is a biochemical material that improves the structural support of plants [72]. Furthermore, it is the second abundant biopolymer after cellulose that has aromatic molecule structure and forms ester linkage with hemicellulose. Lignin molecules consist of three precursors as active functional groups, namely coniferyl alcohol (G), p-coumaryl alcohol (H), and synapyl alcohol (S). The dominant linkage in lignin is aryl ether linkage (β-O-4) with about 50%. This linkage is easier to cleave during lignin conversion and depolymerization [137]. Furthermore, lignin is responsible for UV

Table 4 – Chemical compositions of some natural fibers [20,103–125].

Type of fiber	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Ash (%)	Silica (%)	Wax (%)	Pectin (%)
Rice	28–57 [20,106]	12–19 [20,106]	23–33 [20,103–106]	15–20 [20]	9–14 [20]	8–38 [103–106]	–
Wheat	29–51 [20,106]	16–21 [20,106]	15–32 [20,103,106]	4.5–9 [20]	3–7 [20]	–	–
Barley	31–45 [20]	14–15 [20]	24–29 [20]	5–7 [20]	3–6 [20]	–	–
Ost	31–48 [20]	16–19 [20]	27–38 [20]	6–8 [20]	4–6.5 [20]	–	–
Rye	33–50 [20]	16–19 [20]	27–30 [20]	2–5 [20]	0.5–4 [20]	–	–
Citrullus lanatus	53.7 [107]	10.1 [107]	12.5 [107]	2.17 [107]	–	3.2 [107]	–
Sida mysorensis	53.36 [108]	9.46 [108]	15.23 [108]	3.33 [108]	–	0.86 [108]	–
Momordica charantia	61.2 [109]	4.8 [109]	17.3 [109]	2.24 [109]	–	1.1 [109]	–
Sugar	32–48 [20]	19–24	27–32	1.5–5	0.7–3.5	–	–
Bamboo	26–73.83 [20,106,110]	10.15–36.88 [103,106,110,111]	12.49–31 [103,104,106,110]	1.7–5 [20,111]	0.7–3.51 [20,111]	–	–
Esparto	33–38 [20]	17–19 [20]	27–32 [20]	6–8 [20]	–	–	–
Sabai	–	22 [20]	24 [20]	6 [20]	–	–	–
Congon grass	34.23 [112]	26.99 [112]	36.23 [112]	–	–	–	–
Cortaderia selloana grass	53.7 [113]	10.32 [113]	14.43 [113]	4.2 [113]	–	3.1 [113]	–
Cyperus pangorei	68.5 [114]	17.88 [114]	–	3.56 [108]	–	0.17 [119]	
Phragmites communis	44–46 [20]	22–24 [20]	20 [20]	3 [20]	2 [20]	–	–
Seed flax	43–47 [20,115,116]	21–23 [20,115,116]	24–26 [20,115,116]	5 [20,115,116]	–	–	–
Fiber flax	71 [103–108]	2.2 [103–108]	18.6–20.6 [103–108]	–	–	1.5 [103–106]	2.3 [115,116]
Kenaf	31–57 [20,110]	9–21.2 [20,110]	20.3–33.9 [20,110]	2–5 [20,108–110]	–	–	–
Jute	45–71.6 [20,109]	21–26 [20,109]	13.6–21 [20,115,116]	0.5–2 [20,115,116]	–	0.5 [103–106]	0.2 [115,116]
Hemp	57–77 [20,109]	3.7–13 [20,106,107,110]	14–22.4 [20,106,107,110]	0.8 [20,115,116]	–	0.8 [103–106]	0.9 [115,116]
Sun Hemp	41–48 [110]	22.7 [110]	8.3–13 [110]	–	–	–	–
Ramie	68.6–91 [20,103,106–108]	0.6–0.7 [103–108]	5–16.7 [20,103–106]	–	–	0.3 [103–106]	1.9 [115,116]
Banana	60–65 [110]	5–10 [110]	19 [110]	–	–	–	–
Bagasse	55.2 [103–106]	25.3 [103–106]	16.8 [103–106]	-	-	-	-
Sorghum bagasse	42.36 [111]	24.98 [111]	30.67 [111]	–	–	–	–
Kenaf	37–49 [20,115,116]	15–21 [115,116]	18–24 [115,116]	2–4 [115,116]	–		–
Jute	41–48 [20,115,116]	21–24 [20,115,116]	18–24 [20,115,116]	0.8 [20,115,116]	–	–	–
Abaca	56–63 [20,103–110]	7–9 [20,110]	15–25 [20,110]	3 [20,117,118]	–	3 [103–106]	–
Sisal	47–78 [20,110]	7–11 [20,103–106,110,115,116]	10–24 [20,103–106,110,115,116]	0.6–1 [20,115,116]	–	2 [103–106]	10 [115,116]
Curaua	73.6 [103–106]	7.5 [103–106]	9.9 [103–106]	–	–	–	–
Pineapple	81 [103–106]	12.7 [103–106]	–	–	–	–	–
Henequen	77.6 [115,116]	13.1 [115,116]	4–8 [115,116]	–	–	–	–
Areca palm leaf stalk	57.49 [117]	7.27 [117]	18.34 [117]	0.71 [117]	–	–	–
Agave Americana C. fiber	68.54 [118]	6.08 [118]	18.41 [118]	3.29 [118]	0.56 [118]	–	–
Sansevieria	79.7 [119]	10.13 [119]	10.15 [119]	1.4 [119]	–	0.86 [119]	–
Water Hyacinth	65.07 [120]	11.38 [120]	15.07 [120]	–	–	–	–
Cotton linter	99–95 [20]	0.7–1.6 [20]	1–3 [20]	0.8–2 [20]	–	–	–
Cotton	82.7–90 [103,106,110]	–	5.7 [103–106,110]	–	–	0.6 [103–106]	–
Coir	32–43 [103–106,110]	40–45 [103–106,110]	0.15–0.25 [103–106,110]	–	–	–	–
Kapok	64 [103–106]	–	23 [103–106]	–	–	–	–
Rice husk	35–45 [103–106]	20 [103–106]	19–25 [103–106]	–	–	14–17 [103–106]	–

(continued on next page)

Table 4 – (continued)

Type of fiber	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Ash (%)	Silica (%)	Wax (%)	Pectin (%)
Calotropis gigantea fruit bunch fibers	64.47 [121]	13.56 [121]	9.64 [121]	3.13 [121]	–	–	–
Oil palm empty fruit bunch	65 [110]	19 [110]	–	2.0 [110]	–	–	–
Oil palm frond	56 [110]	20.48 [110]	27.5 [110]	2.4 [110]	–	–	–
Areca palm fruit fiber	57.35–58.21 [122]	23.17–24.16 [122]	13–15.42 [122]	–	–	–	0.2 [122]
Tamarind tree fruit fiber	72.84 [122]	15.38 [122]	11 [122]	–	–	–	–
Coconut	32–43.8 [64]	40–45	0.15–20 [64]	–	–	–	3–4 [64]
Palmyrah	70–83 [64,123]	5–12.7 [64,123]	14.03 [64,123]	0.64 [64,123]	–	–	–
Limonia Acidissima	41.28 [124]	28.31 [124]	27.01 [124]	1.2 [124]	-	-	-
Coniferous/soft wood	20–64 [20,110]	14–34 [20,110]	7–40 [20,110]	<1 [20,110]	–	–	–
Deciduous/hard wood	38–49 [20]	23–37 [20,110]	19–30 [20,110]	<1 [20,110]	–	–	–
Acacia planifrons bark fiber	73.1 [10]	12.04 [10]	9.41 [10]	0.57 [10]	–	–	–
Coccinia grandis L	62.35 [125]	15.61 [125]	13.42 [125]	0.79 [125]	–	–	–

degradation and char formation of natural fibers [130]. According to Table 4, coir fiber has one of the highest quantity of lignin, and similar result was also reported by Gu [138] and Wang and Chen [139]. Coir has lower cellulose and hemicellulose content with microfibrillar angle that affects the properties of a plant which include strength, resilience, damping, wear, resistance to weathering and high elongation at break [3].

Lignin is usually removed during the pulping process in the pulp and paper industry because it is an undesirable part of pulping raw materials. Pulp with desirable kappa numbers could be reached by complete delignification process. Furthermore, the delignification process of samples with higher lignin content requires high amount of chemical energy. While samples with lower lignin content are suitable for delignification at milder pulping conditions (lower temperatures and chemical charges) [131]. High lignin content could be used as a source of adhesive in binder less fiber board. In addition, it could also be extracted for further utilization in value added product such as adhesives, biosurfactant, antimicrobial agent, fine chemicals, carbon fiber, lignosulfonate for water reducer etc.

5. Anatomy and morphology

Plant fibers are rarely found as individual cells, however, most single fibers are gathered into bundles. Furthermore, the size of the bundles in plants could be used to determine the age of a plant [140]. Furthermore, the nature of a single fiber depends on the shape, size, orientation and thickness of the cell wall [141]. Natural fibers are of low energy consumption and density, non-abrasive properties, low cost, renewability, biodegradability and abundant availability [63]. Their diameter is not constantly depended on fiber growth factors and preparation technology methods, and harvest time [142]. Furthermore, Messiry [143] stated that even though fibers are obtained from the same material, the diameters are different. The cross-sectional shape of fibers vary widely from non circular shapes such as a kidney bean shape for cotton and are reasonably circular for wool [144], and the number of single fibers determine the size of each bundle [145]. Based on Munawar et al. [39] observations on natural fiber bundles, noncircular shapes on the cross section of the bundles were found in ramie bast, pineapple leaf, kenaf bast, sansevieria leaf, abaca leaf and coconut husk fibers (Fig. 4). Ramie bast fiber has a smaller bundle diameter compared to the others with a cell wall thickness of about 1–5 mm, while lumen diameter of fibers was 0.1–18 mm. In addition, fiber density, mechanical and dimensional properties are affected by the difference between lumen diameter and single fiber shape.

Based on the chemical composition analysis, each type of natural fiber from different plants has different characteristics. There were variations in the value of fiber length, cell wall thickness, lumen and fiber diameter between the same species. Furthermore, the measurement results that was reported by different studies showed the variation of these values. Some factors that causes it include the growth site of natural fiber, method of extraction, and age of plant. Bamboo is classified as long fibers with length that is more than 3000 μm

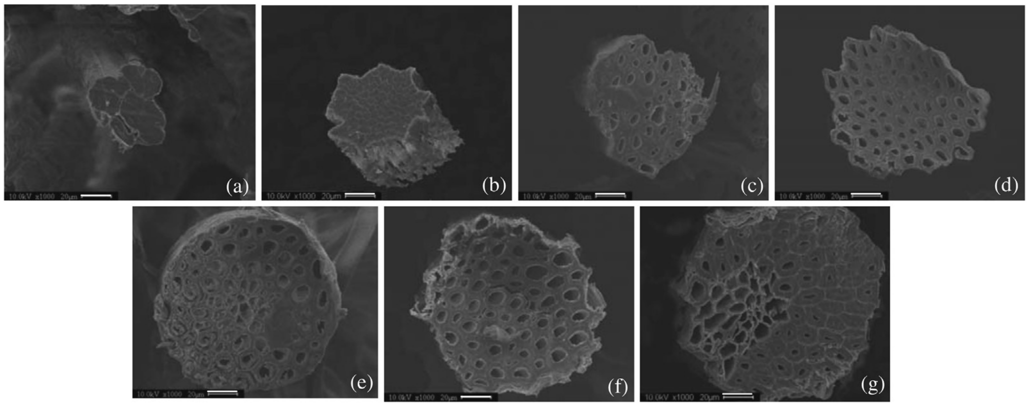

Fig. 4 – Scanning electron micrographs showing typical shape of cross section in the nonwood plant fiber bundles at × 1000 magnification. a RB, b PL, c KB, d SaL, e CH, f AL, g SiL. Bars 20 μm (Reprinted with permission from Springer Nature, License Number: 5071141102426) [39].

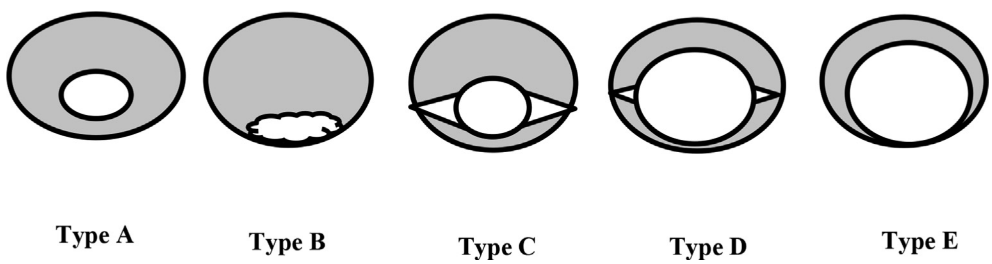

Fig. 5 – Type fibrovascular bundles from 14 palm genera [148,149].

[146]. Fiber with high cell wall thickness tends to contain high lignin content. While lumen cell produces fiber with hollow structure that are not found in synthetic fibers [147].

Zhai et al. [148] investigated fibrovascular bundles from 14 palm genera (18 species) and they found that the diameter, shape, and localization of vascular tissues on the transverse section varied among the species. In addition, those fibrovascular bundles consist equally of thick-walled sclerenchyma fibers and vascular tissue, which are classified into 3 types, namely type A – rounded in the central region, type B – angular in the marginal region, and type C–aliform in the central region (Fig. 5). However, Hakim et al. [149] found 2 new types of fibrovascular bundles in 2 species of *Salacca sumatrana* and *Salacca zalacca*, which also belong to the palm genera, and are categorized into type D – the vascular tissue was round with wider sclerenchyma fibers surounding it, and type E – the shape of vascular was oval, but the sclerenchyma fibers did not encircle vascular tissue. The diamater of the fibrovascular bundles increased linearly with the ratio of vascular tissue to the entire transverse sectional area.

6. Future perspective

Indonesia and Malaysia have various natural fibers, and some are already planted commercially, but most of them have not been utilized optimally. In order to increase their economic values, these abundant natural fiber resources need to be explored and exploited. Industries which use natural fibers as raw materials have provided Indonesia or Malaysia with a significant source of income. To boost economic growth and the well-being of the people of Indonesia or Malaysia, it must be continuously established. Numerous studies on the use of natural fibers as reinforced composites in dentistry and as textile tools have already been conducted in Indonesia. While in Malaysia, the natural fiber has been used as composite and automotive manufacture.

To overcome the weaknesses of natural fiber materials, modification or pretreatment of natural fiber could be used to increase matrix bonding, reinforcement and composite strength [150–154]. Moreover, in order to overcome the low degradation temperature of natural fiber (~200 °C) before processing with thermoplastics with a temperature that is up to 200 °C, the interfacial treatment (surface treatment resins, additive, coating) need to be improved [64,155].

7. Conclusion

Natural fibers that are renewable and environmentally friendly source of raw materials to create environmental friendly products have played an important role in human civilization. Eco-friendly composites mainly light weight composites and textiles are two of the most popular uses of natural fibers in Indonesia, with ramie and kenaf being the most promising for textile and automotive components. In

Malaysia, natural fiber such as kenaf, pineapple also biomass waste from oil palm industry is attractive for further developed for eco-friendly composite. The fascinating properties of natural fibers include lesser density thus lighter weight, more considerable cost, biodegradable, abundantly available, minimal health hazards during processing, reasonably good specific strength and modulus, good thermal, good acoustic insulation characteristics, good physical properties, and ease of availability. To enhance and improve its sustainability, the physical, mechanical, chemical, morphological, and anatomy properties of natural fiber should be considered for appropriate optimal utilization. Chemical properties of natural fiber, such as cellulose in the cell wall, have a strong relationship with tensile properties and density. Natural fibers, despite their advantages, have issues such as low longevity, non-uniform properties, poor adhesion, moisture absorption, and wettability. In the utilization as composites, the hydrophilicity of natural fibers leads weak adhesion with hydrophobic matrices thus low mechanical properties and poor processability resulted. As a result, to expand the range of applications for these fibers, the weaknesses should be addressed using suitable technologies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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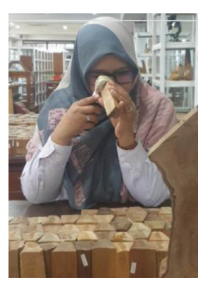

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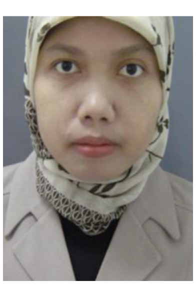

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