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WOOD STRUCTURE AND FUNCTION (S HIZIROGLU, SECTION EDITOR)

Nonwood-Based Composites

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Abstract Nonwood fibers are derived mostly from fast-growing plants. For the past few decades, nonwood plant fibers have received much attention, especially for composite material applications, because of their low cost, low density, high specific strength, good mechanical properties, nonabrasiveness, eco-friendliness, and biodegradability. This article reviews the performance of nonwood fibers found mostly in Asia, as well as issues regarding their bonding. Because various classifications of nonwood exist, this article sorts nonwood fibers based on previous classifications with some modifications, accounting for the availability of these fibers in Asia. The mechanical and physical properties of nonwood-based composites such as fiberboard, particleboard, and veneer-based laminated products also are reviewed and discussed. All fibers demonstrate certain advantages over conventional composites, with some having better mechanical and physical properties. This article also highlights the issues and challenges regarding the use of nonwood fibers as composite materials.

Keywords Nonwood fibers · Composites · Asian regions · Physical properties · Mechanical properties

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Introduction

Nonwood fibers are one of the important alternative resources for fibrous material in the twenty-first century because of the shortage of trees and increasing global demand for fibrous material [1]. These plant fibers have been receiving tremendous attention for decades, and interest in them is still growing strongly. An example of nonwood fibers is "field crops" or agricultural crops grown for their fibers. Such fibers have existed for hundreds of years and traditionally have been used to make paper, cloth, rope, and composite products, ensuring their continued existence [2]. Bamboo, another example of nonwood found in the forest, has attracted global interest recently. Biomass, on the other hand, is fiber residue derived from plants either at the plantation or at the processing mill. Very often, biomass is associated with biorefinery activities for energy production.

For decades, materials scientists and engineers have been exploring other uses for natural fibers in composite materials. This article reviews the basic properties of some nonwood fibers, particularly those found in Asia, and highlights issues regarding bonding with polymer, surface wettability, buffering capacity, and the influence of these fibers on board properties. The properties of particleboard, fiberboard, laminated board, and plywood manufactured from various types of nonwood fibers are compared.

Types of Nonwood Fibers

Nonwood plants are either dicotyledonous or monocotyledonous and may be divided into various classifications. Previous studies categorized plant fibers based on their origin and divided them into two main groups [3•, 4, 5, 6••]:

Conventional plant fibers, such as cotton, kapok, flax, jute, hemp, ramie, kenaf, sisal, abaca, henequen, coir, and bamboo

Nonconventional plant fibers or agro-based fiber residues, such as corn stalk; wheat straw; rice straw; rice husks; sugarcane/bagasse; pineapple leaf; banana pseudostem; coconut stem; and oil palm fibers from the stem/trunk (OPT), fronds, and empty fruit bunch (EFB)

Most nonwood fibers are derived from plants that are fast growing and require months (kenaf, jute, flax, and hemp) to years (oil palm, coconut, bamboo, abaca, and sisal) to reach maturity. Compared with softwood, which takes more than 20 years, and hardwood, which requires more than 30 years to reach maturity, nonwood growth cycles are significantly shorter [7]. Because of the differences in maturity periods, nonwood fiber plants have various stem sizes: slender, e.g., kenaf, jute, hemp, wheat straw, and bagasse; moderate, e.g., bamboo; and large, e.g., oil palm trunk and coconut trunk. This variation explains why the processing lines used for each type of nonwood fiber differ from one another.

Traditionally, most nonwoods, including bagasse, wheat and rice straw, bamboo, kenaf, hemp, jute, sisal, abaca, cotton linters, and reeds, have been used worldwide to manufacture pulp and paper [8]. Besides their use in papermaking, nonwood plants have served as potential raw materials in value-added panels such as medium-density fiberboard (MDF), particleboard, oriented strand board (OSB), plywood, and laminated products. Some nonwood fibers are being used as reinforcement in the production of wood polymer composites (WPCs). Most of these fibers are processed easily into pulp, particles, strands, and sawdust to produce MDF, particleboard, OSB, and WPC panels, respectively; however, some limitations exist in using them to produce plywood and laminated materials. Except for oil palm trunk and bamboo, most nonwood plants have a relatively small diameter, approximately 1 to 5 cm, making them impractical for processing into veneer, lumber, or strips. In this article, we categorize nonwoods based on their origin as (1) *agricultural-based or agro-fibers*, (2) *plant biomass*, or (3) *grass*. Figure 1 shows some examples of plants based on these categories.

Agro-Fibers

The most popular and frequently cited agro-fibers belong to a group known as bast fibers. These fibers are derived from plants with established and specific end uses because of their properties. Examples are jute, hemp, flax, kenaf, and ramie. Sisal, abaca, and henequen are other examples of agro-fibers that are derived from leaves [4, 5]. The presence of these crops usually is linked to a specific country, climate, or culture. Hemp and flax are found mainly in Europe, and sisal is found mainly in Tanzania and Brazil, abaca in the Philippines, and jute in Bangladesh and India [9]. Although China has a unique agricultural practice whereby all types of hard fibers (hemp, flax, ramie, jute, kenaf) have been grown for more than 100 years, planted areas have diminished significantly as a result of an increase in food crop cultivation. Kenaf, on the other hand, is an attractive agro-fiber with a long history of cultivation in the USA, Bangladesh, India, Thailand, Australia, Indonesia, and Malaysia and, to a lesser extent, in southeast Europe, some parts of Africa, and Brazil [10]. In different parts of the world, many other names have been used for kenaf, including *mesta* (India), *java jute* (Indonesia), *stock root* (South Africa), and *ambary* (Taiwan) [11]. Jute is a long, soft, and shiny fiber that can be spun into coarse, strong threads and is one of the cheapest natural fibers. It also is one of the most versatile, eco-friendly, durable, and antistatic fibers. Normally, jute plants are retted by the same method used for flax [5]. On the international market, the names *jute* and *kenaf* are used interchangeably because of their close resemblance.

Plant Biomass

Coconut trunk and coir, two types of biomass from coconut trees, have been on the market for decades. Whereas the trunk has been used by the timber industry to make laminated products and plywood, coir is the most popular fiber used in manufacturing high-quality mattresses. Sri Lanka and the Philippines are the main exporters of this material. Coir fibers are coarse and short and are extracted from the outer shell of coconuts. Of all the commercial natural fibers, coir is reported to be the most resistant to microbial action and salt water damage. Its low decomposition rate is a key advantage in making durable geotextiles [12].

Oil palm (*Elaeis guineensis* Jacq.), a monocotyledonous plant, normally presents as a single stem approximately 20 m in height. Malaysia and Indonesia are the largest producers of palm oil in the world. Traditionally, the main product of oil palm has been palm oil, with the remaining biomass waste either burned (as the main energy source for power generation in palm oil mills) or used as organic fertilizer through natural decomposition [13, 14]. In addition, EFB is also used in soil mulching as an organic nutrient to reduce the input of inorganic fertilizer [15]. Today, oil palm plantation generates huge amount of biomass in the form of trunks (after a 25-year replantation scheme) and fronds (with every tree pruned once a month). In addition, EFBs are generated from the palm oil factory every day [16, 17].

Bagasse, a by-product of sugar milling, is the crushed remnants of sugarcane stalks that remain after the juice is extracted. It consists of three parts—pith, fiber, and rind—mixed in different proportions, with considerable variation in the shape and size of these three components [18].

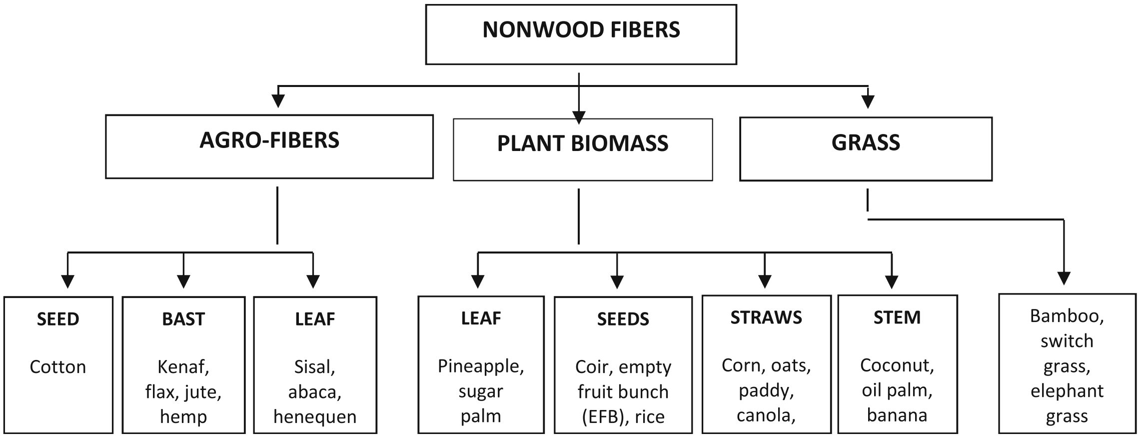


Fig. 1 Classification of nonwood fibers

Straw, an agricultural by-product, is composed of the dry stalks of cereal plants after the grain and chaff have been removed. Straw makes up about half the yield of cereal crops such as barley, oats, rice, rye, and wheat. Currently, there are huge quantities of unused straw residues around the globe. In 1999, China, India, and the USA appeared to be the major producers of straw residues, mainly wheat and rice straws [19]. However, in 2012, Europe was the leading exporter of straw husks at 783,485 t [20]. Straw has many uses, including fuel, livestock bedding and fodder, thatching, and basket making. It usually is gathered and stored in straw bales.

Another agricultural residue of interest is rice husk, a by-product of rice mills. The husk is the hard protective covering on a rice grain and is available throughout the year. Currently, rice husks are used in many applications, including composites, fertilizer, insulation material, and fuel [21].

Grasses

Among the many types of grasses, bamboo is the most popular. It has been identified as one of the most promising crops because of its great strength: the strength-to-weight ratio of bamboo is far higher than that of structural steel, aluminum alloy, cast iron, timber, and concrete, proving that it has a very efficient load-bearing capability [22]. Bamboo is a versatile, strong, renewable, and environmentally friendly material. It is a member of the grass family, Gramineae, and the fastest-growing woody plant on Earth because of its unique rhizome-dependent system [23, 24]. As stated by Chaowana [24], bamboo is distributed mostly in the tropical, subtropical, and temperate zones of all continents except Europe and North America. However, in recent years, bamboo was introduced to North America, Europe, and Australia [25, 26]. Bamboo has a wide range of applications: it is used as a source of food and energy and as a material for handicrafts, construction, and vehicle parts, as well as for ornamental and many other purposes [24, 27].

Properties of Nonwood Fibers

Bulk Properties

For all fiber-based products, both density and moisture content are crucial because they determine the actual amount of fibers and resin/matrices to be used. Bulk density is defined as the weight of a cubic meter of a loose volume of fibers, which varies with moisture content [28]. Most nonwood fibers are denser than wood (Table 1); however, most of these fibers, particularly those from biomasses, have greater density variations. For example, bagasse varies from 0.52 to 1.47 g/cm^3 [46] and wheat straw from 0.02 to 1.10 g/cm^3 in density [48]. Bamboo fiber has a higher density than most wood.

Anatomic Properties Specific

Agro-fibers were observed to have a relatively higher cellulose content (as high as 80 % for hemp) compared with plant biomass (a mere 63 % for EFB) and forest products (48 % for bamboo). With regard to cellulose and lignin, both plant biomass and bamboo have almost the same amount. It also was observed that almost all agro-fibers contain more cellulose than does wood.

Studies by Ashori [1] indicate that the dimensions of nonwood fibers are between those of hardwoods and softwoods. As shown in Table 1, the length of agro-fibers ranges from 0.50 to 600 mm, whereas that of biomass fibers ranges from 0.66 to 250 mm. According to Blackburn [62], fibers from fruits and seeds are few centimeters long, whereas fibers from stems and leaves are much longer, sometimes reaching more than 1 m long. Oil palm-based fibers are significantly shorter than fibers from other plant biomasses, bamboo, and hardwoods. Conversely, plant biomass fibers have a cell wall thickness similar to that of agro-fibers and some wood species. In many cases, bamboo has a thicker cell wall and longer fibers than any wood or nonwood.

Table 1 Properties of nonwood fibers

Materials	Density (g/cm^3)/ specific gravity	Cellulose (%)	Lignin (%)	Length (mm)	Diameter (μm)	Cell wall thickness (μm)	Lumen width (μm)
Kenaf whole stem	*0.32–0.037* [29]	40.2–53.8 [30, 31]	13–21 [30, 31]	1.29 [30]	22.1 [30]	4.3 [30]	12.7 [30]
Kenaf core	0.1 [10] *0.28–0.31* [29]	47.4–49.0 [31, 32]	19.2–19.4 [31, 32]	0.7–1.1 [30, 31, 33, 34]	21.4–38 [30, 33, 34]	3.3–5.6 [30, 34]	11–21 [30, 34]
Kenaf bast	1.3–1.5 [35, 36]	55.0 [31]	14.7 [31]	1.2–3.6 [30, 31, 34, 37]	21.3–28.6 [30, 34, 37]	6.2–6.9 [34]	8–16 [30, 34]
Hemp	1.48 [36]	80 [38]	4 [38]	22 [38]	20 [38]	–	–
Jute	1.45 [36]	61–71 [39]	12 [39]	0.5–6.0 [39]	26–30 [39]		
Flax	1.54 [36]	60–70 [39]	2–3 [39]	6–65 [15]	20 [15]		
Sisal	0.76–1.45 [35, 36]	70 [15]	–	180–600 [40]	100–300 [41]		
Oil palm trunk	0.27–0.44 [42•]	41.0 [43•]	24.5 [43•]	0.66 [43•]	16.6 [43•]	8.00 [43•]	–
Oil palm frond	–	49.8–56.0 [43•, 44]	20.5 [43•]	–	–	–	–
Oil palm EFB	0.18–1.32 [45]	50.5–62.9 [43•, 46]	17.8 [43•]	0.99 [46]	19.1 [46]	3.38 [46]	–
Bagasse	0.52–1.47 [46]	55.75 [47]	20.5 [47]	1.59 [47]	21.0 [47]	5.6 [47]	9.7 [47]
Wheat straw	0.02–1.10 [48]	43.2–49.8 [49, 50]	19.6–21.2 [49, 50]	1.14–1.18 [49, 50]	13.6–19.3 [49, 50]	4.39 3.96 [49, 50]	5.7–10.5 [49, 50]
Canola straw	0.27–1.58 [51]	41.1 [52]	17.2 [52]	1.21 [53]	28 [53]	7.43 [53]	11.9 [53]
Coir	1.15 [54]	44.2–33.2 [40, 44]	32.8–20.5 [40, 44]	50–250 [40, 55]	270 [55]	–	–
Bamboo (5 years)	0.58–0.95 [56]	46–48 [57]	22.9–23.0 [57]	2.0–2.4 [57]			
Outer	0-81–0.84 [56]			1.70–2.03 [56]	18.5 [56]	7.03 [56]	5.44 [56]
Middle	0.63–0.66 [56]			2.06–2.32 [56]	22.4 [56]	8.43 [56]	5.51 [56]
Inner	0.58–0.59 [56]			1.86–2.39 [56]	19.6 [56]	6.80 [56]	5.96 [56]
Softwood	*0.35–0.61* [58]	30–60 [59]	21–37 [59]	–	–	–	–
Hardwood	*0.40–0.72* [58]	31–64 [59]	14–34 [59]	–	–	–	–
Hardwood (aspen)	–	–	–	0.50–1.35 [60]	13–37 [60]	1.3–5.3 [60]	–
Rubberwood PB260–25 years	*0.60* [61]	44 [61]	23 [61]	1.34 [61]	27 [61]	6.0 [61]	14 [61]

Specific gravity is presented in italic to differentiate the density and specific gravity

Strength Properties

Table 2 lists the mechanical properties of nonwood fibers. Most agro-fibers have greater tensile strength compared with plant biomass and bamboo, ranging from 80 to 1191, 71 to 175, and 441 to 800 MPa, respectively. According to Abdul Khalil et al. [31] and Horn and Setterholm [72], a high cellulose content as well as longer fibers and thicker cell walls may be responsible for the high strength of bamboo products. Most agro-fibers have a higher density, which explains the relatively higher mechanical strength of these fibers compared with wood. Kenaf, hemp, jute, and flax have higher tensile strength compared with EFB, bagasse, wheat straw, and coir. However, some agricultural crop fibers, such as jute, have a tensile strength of 370 MPa, slightly lower than that of bamboo [36, 65, 71].

Nonwood fibers have large variations in properties compared with synthetic fibers. Using Young's modulus, Sobczak et al. [73] plotted the tensile strengths of both synthetic and natural fibers (Fig. 2). The values that they observed for natural fibers and wood varied from 7 to 70 GPa [74, 75]. In comparison, values for synthetic fibers range from 70 GPa (short glass fiber/long glass fiber) [76] to 240 GPa (short carbon fiber) [77]. The vast differences found in natural fibers imply that these fibers are more heterogeneous than synthetic fibers. Such inconsistencies have been the biggest constraint on the commercialization of natural fiber-based products.

Bamboo strips were reported to have a modulus of rupture (MOR) ranging from 149.1 to 262.5 MPa and a modulus of elasticity (MOE) comparable to that of softwood (Table 3). Different species and parts (node and internodes) of bamboo result in differences in MOR and MOE [78]; however, there is much less variation along the plant's height. [57]

Bonding of Nonwood Fibers

With regard to polymer matrix composites, there appears to be an optimum level of fiber–matrix adhesion that provides the best composite mechanical properties [83]. A strong fiber–matrix bond is critical for superior mechanical properties in

Table 2 Mechanical properties of some nonwood fibers

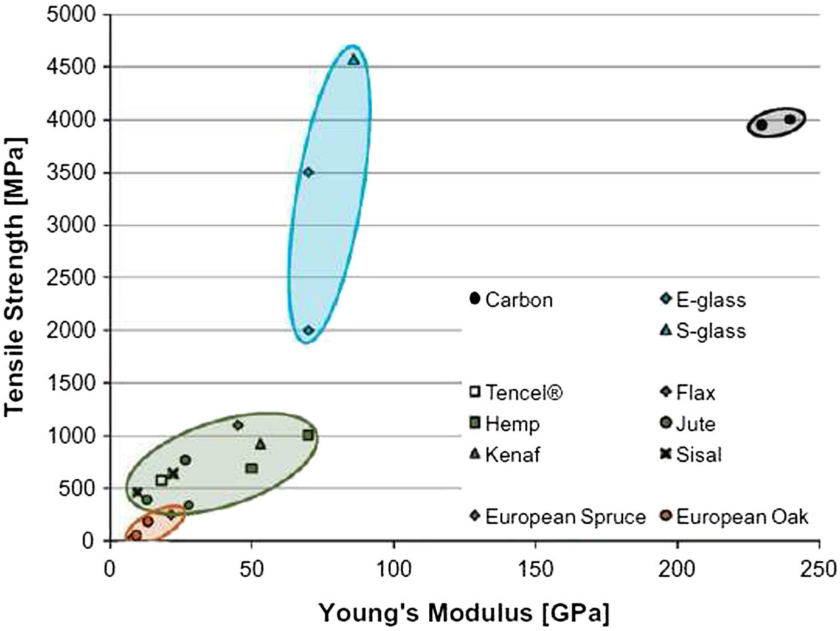
Nonwood	Kenaf bast	Hemp	Jute	Flax	Sisal	Oil palm trunk	Oil palm EFB	Bagasse	Wheat straw	Coir	Bamboo
Density (g/cm^3)/ specific gravity	1.3–1.5 [35, 36]	1.48 [36]	1.45 [36]	1.54 [36]	0.76–1.45 [35, 36]	0.27–0.44 [42•]	0.18–1.32 [45]	0.52–1.47 [46]	0.02–1.10 [48]	1.15 [54]	0.58–0.95 [56]
Tensile strength (MPa)	295–1191 [35, 63]	310–750 [64]	370 [65]	500–900 [66]	80–840 [35, 64]	300–600 [67]	71 [68]	70 [69]	21–28 [70]	106–175 [55, 63]	441–575 [65, 71]
E-modulus (GPa)	22–60 [35, 63]	30–60 [64]	2.5–23 [36, 65]	50–70 [66]	9–22 [35, 64]	15–32 [67]	1.7 [68]	–	–	2–6 [55, 63]	27–36 [65, 71]

composites. The physical properties of lignocellulosic materials are influenced basically by the chemical structure, such as cellulose content, degree of polymerization, orientation, and crystallinity, which are affected by conditions during plant growth as well as by the extraction method used [84, 85]. Unlike wood, nonwood fibers have an enormous amount of variability in their properties depending on the part of the plant from which the fiber is taken, the quality of the plant, and its location. Different fibers have different lengths and cross-sectional areas, as well as different defects, such as microcompressions, pits, or cracks [86]. To achieve uniformity and flexibility, some researchers conducted surface modification on the fibers by dissolving the microfibrils in solvent, followed by precipitation under controlled conditions, by increasing the wettability of the fiber surfaces through pretreatment with chemicals, or by adding coupling agents [86, 87].

Lignocellulosic materials have a strong polar character, rendering them hydrophilic, whereas thermosetting and thermoplastic matrices are hydrophobic in nature. Hence, when these materials are combined, compatibilizers or coupling agents must be used to improve the adhesion between fiber and matrix [88]. Unlike wood, bonding of most agro-fibers and biomasses is relatively more difficult, mainly because of their decreased wettability. A typical example is demonstrated in Fig. 3, which shows poor interfacial bonding between a coir fiber and epoxy. Mohanty et al. [90] performed a comprehensive review of the influence of various surface modifications of agro-fibers, such as henequen, jute, and coconut (coir) fibers, and their effects on the performance of biocomposites. According to the authors, the main drawback of natural fibers is their hydrophilicity, which reduces their compatibility with hydrophobic polymer matrices. The hydrophilic nature of biofibers results in biocomposites with enhanced water absorption characteristics, making them less useful for many applications. The natural waxy substance present on the fiber's surface contributes greatly to ineffective fiber–polymer matrix bonding and to poor surface wetting. The presence of free water and hydroxyl groups, especially in the amorphous region, reduces the ability of natural fibers to adhere to most binder resins. High water and moisture absorption by the fibers causes swelling and a plasticizing effect, resulting in dimensional instability and poor mechanical properties.

Untreated natural fibers usually are covered by a layer probably composed mainly of waxy substances [91]. This layer is not distributed evenly along the fiber's surface, and its thickness varies from point to point. Studies by Sreekala et al. [92] showed that the surface of the esterified materials becomes smoother compared with that of untreated materials. Removal of the waxy substance on the surface of lignocellulosic materials makes the fiber's surface smoother after esterification (Fig. 4).

Fig. 2 Ashby plot presenting the absolute tensile strength vs. Young's modulus for various fiber types (source: after Sobczak et al. [73])



Our study on the pretreatment of oil palm EFB fibers showed tremendous improvement in fiber surfaces when treated with NaOH [94, 95]. Scanning electron microscope (SEM) images of untreated and treated fibers (Fig. 5a, b) clearly show fibrils that are aligned, forming a packed structure. The untreated fiber has a much rougher surface, with layers of impurities, suspected to be lignin and wax, covering the surface.

Table 3 Mechanical properties of some nonwoods

Materials	Density (g/cm^3)	Static bending		Compression strength			
		MOR (MPa)	Young's modulus (MPa)	Longitudinal ∥		Tangential ⊥	
				Compressive stress (MPa)	Young's modulus (MPa)	Compressive stress (MPa)	Young's modulus (MPa)
Bamboo strip (5 years) [57]							
Bottom	0.75	186.2	13,162	93.6	4896	34.1	533
Middle	0.78	184.8	13,410	86.6	4980	33.6	527
Top	0.76	183.4	13,307	85.8	5185	35.3	552
Bamboo strip [78] (*Schizostachyum brachycladum*)							
Node	0.67	149.1	17,368	–	–	–	–
Internodes	0.58	262.5	20,890				
Rubberwood [79] (*Hevea brasiliensis*)	0.46–0.65	66	9240	32	–	5	–
(12 % MC) [80]	*0.58*			39	4100		
(66 % MC) [80]	–			27	3500		
20-mm thickness							
Tropical hardwood Chengal [81] (*Neobalanocarpus heimii*)	0.92–0.98	149	19,600	75.2	–	12	–
Softwood Pine [82] (*Pinus radiata*)							
4-mm thickness	0.39	–	19,800	–	–	–	–
8-mm thickness	0.38		14,800				

Italic indicates species name of the plants

∥ parallel to the grain direction, ⊥ perpendicular to the grain direction

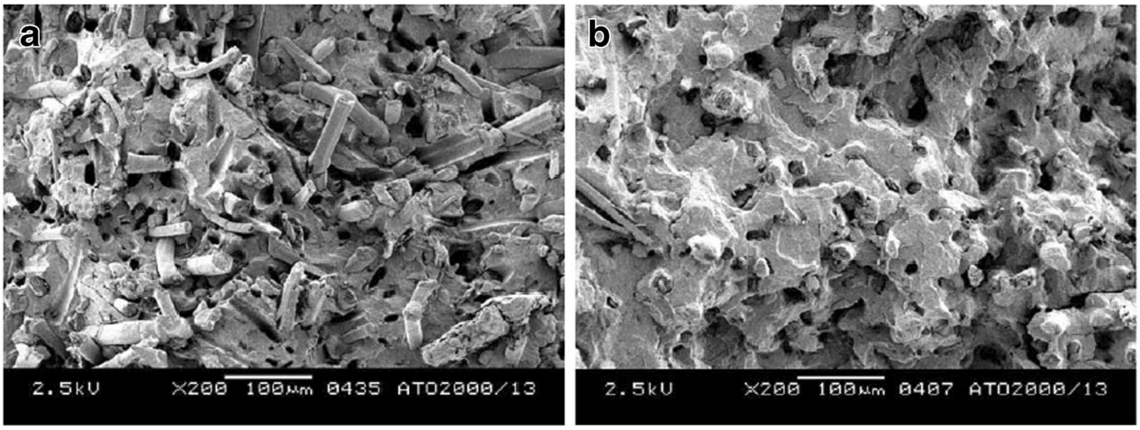


Fig. 3 SEM ×200 of 30 wt% agro-fiber/PP composite. **a** Without a coupler. Voids and pull-outs are seen. **b** With a 3 % Epolene G-3015 coupler. Good fiber wetting and interblocking are seen (source: Keener et al. [89])

Wettability and Buffering Capacity

Our research shows that wetting is necessary but not always sufficient for a strong bond and that contact angle detects changes in surfaces due to contamination or chemical modification [29, 95, 96]. Adhesion properties, such as wettability, pH, and buffering capacity, of wood and nonwood are among the factors influencing the properties of most composite panels.

In conventional biocomposite manufacturing, thermosetting resins such as urea formaldehyde (UF), melamine urea formaldehyde (MUF), and phenol formaldehyde (PF) commonly are used as binders. These adhesives are sensitive to the pH of the substrate because the rate of cross-linking of most thermosetting adhesives is pH dependent [97]. Therefore, most adhesives are formulated to adapt to the acid range and buffer capacity of the substrate. The pH- and acid-buffering capacities of aqueous extracts from agro-fibers are reported to be significantly greater than those of softwoods, and in the presence of such materials, resin gel time increases greatly [98–100]. Paridah [6••] extensively studied both the wettability and buffering capacity of various nonwood fibers and concluded that both properties are crucial in determining the performance of the resulting composites. Figures 6, 7, 8, 9, 10, 11, and 12 show the results from studies on the wettability and buffering capacity of bamboo, kenaf, oil palm trunk (OPT), and straws.

Properties of Composites from Nonwood Fibers

Agricultural crops such as kenaf, jute, sisal, and flax, as well as biomass such as bagasse, oil palm fibers, and wheat and rice straws, have great potential in composite manufacturing. The use of these materials in the production of composite panels and paper products now is considered attractive both from an economical (or economic) and environmental point of view. Use of these fiber resources helps protect virgin forests in regions where there is a shortage of wood [103]. In addition,

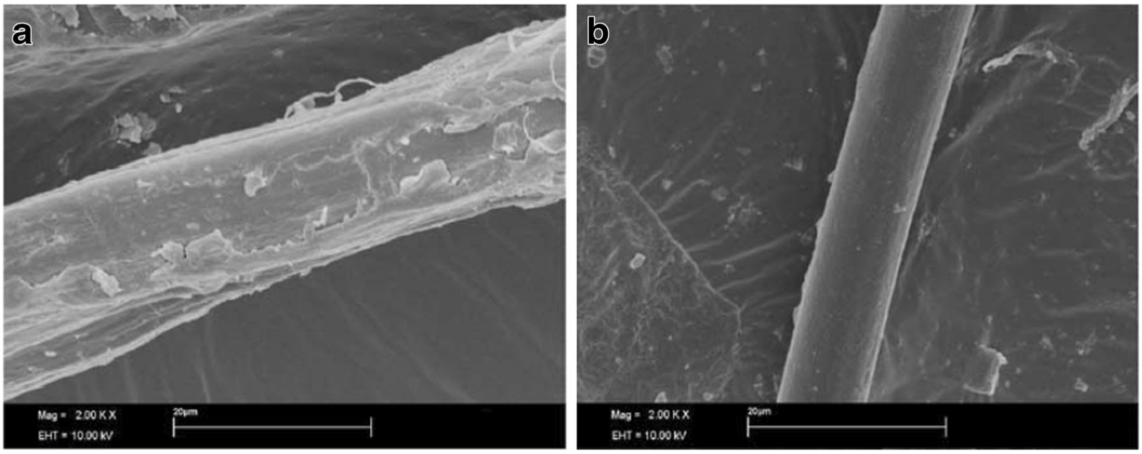


Fig. 4 SEM images of untreated and esterified hemp fiber: **a** untreated and **b** acetylated (source: Tserki et al. [93])

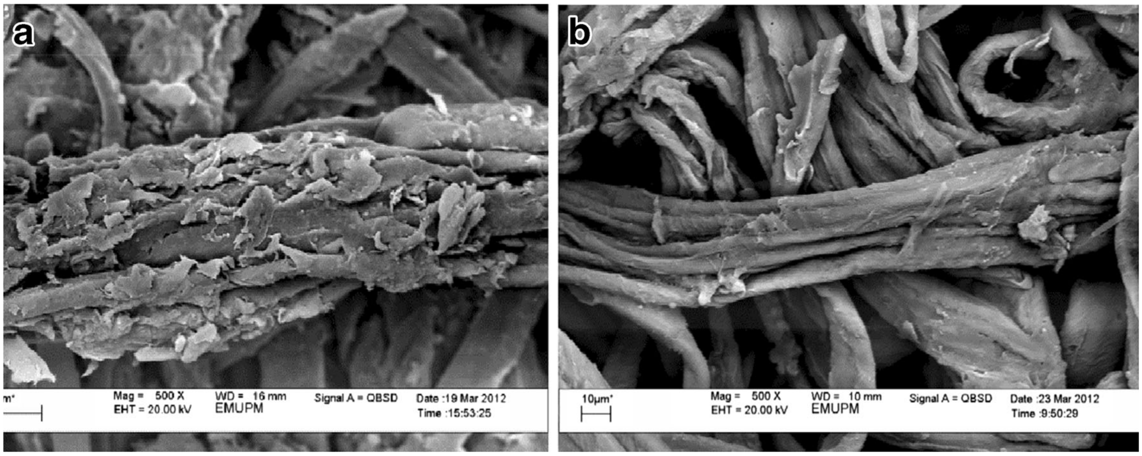


Fig. 5 SEM image of an EFB fiber **a** untreated and **b** after soaking in NaOH (×500 magnification) (source: Norul Izani et al. [94])

large quantities of biomass are available today in many parts of the world where open burning is prohibited [19].

Efforts to convert nonwood fibers into quality products have intensified during the past 20 years because they are inexpensive, have low density, are tough, cause less dermal and respiratory irritation, are easy to separate, and are biodegradable [3•]. Wood-based industries are the most appealing sector for these efforts because nonwoods closely resemble wood fibers and therefore have similar applications in the furniture and construction industries. The following sections review the mechanical and physical properties of some of these products, specifically those of MDF, particleboard, plywood, laminated veneer lumber (LVL), and glued laminated panels.

Fiberboard

The mechanical and physical properties of MDF made from nonwood are similar to those of wood. Table 4 shows the properties of MDF made from different fiber sources. The mechanical properties of agro-fibers and plant biomass are similar; however, in some cases, superior fibers do not necessarily result in superior board. Kenaf bast, for instance, has high density, long slender fibers, and superior tensile strength compared with other natural fibers; however, when it is converted into MDF, the properties of the resulting board are very poor [33, 37]. Kenaf core, on the other hand, has short fibers, a thin cell wall, and a very large lumen size but produces MDF with much greater MOR, MOE, and internal bonding (IB) as well as greater dimensional stability compared with kenaf bast. Paridah [6••] attributed the poor performance of kenaf bast fibers to their low wettability, which limits adhesive penetration and consequently reduces bond integrity. She also concluded that the low fiber density (0.1 g/cm^3), thin cell wall, and large lumen of kenaf core fibers provide better compaction and densification of fibers, which result in the superior performance of kenaf board.

Likewise, the performance of MDF made from biomass with shorter fibers, such as OPT, bagasse, and wheat straw

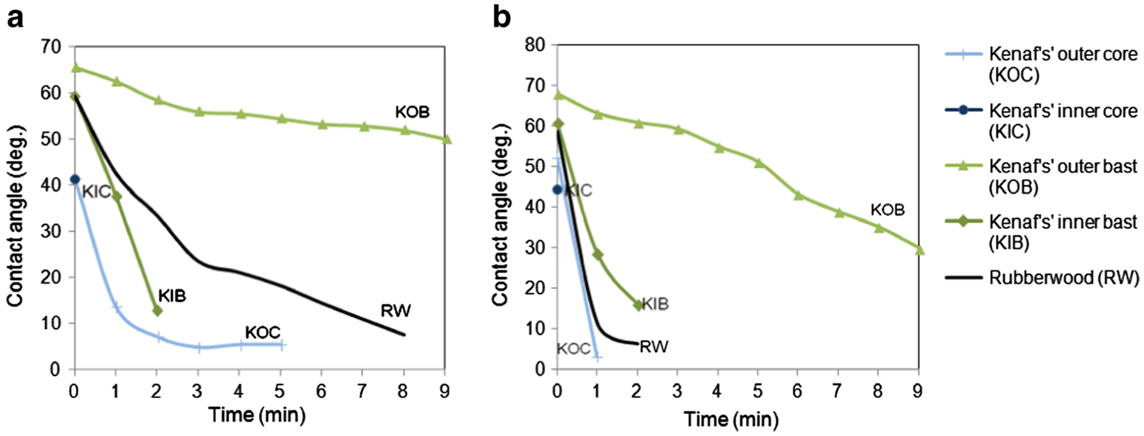


Fig. 6 Contact angles of kenaf using **a** 0.1 N HCl and **b** 0.1 N NaOH solutions on different substrates as a function of time (source: Juliana et al. [29])

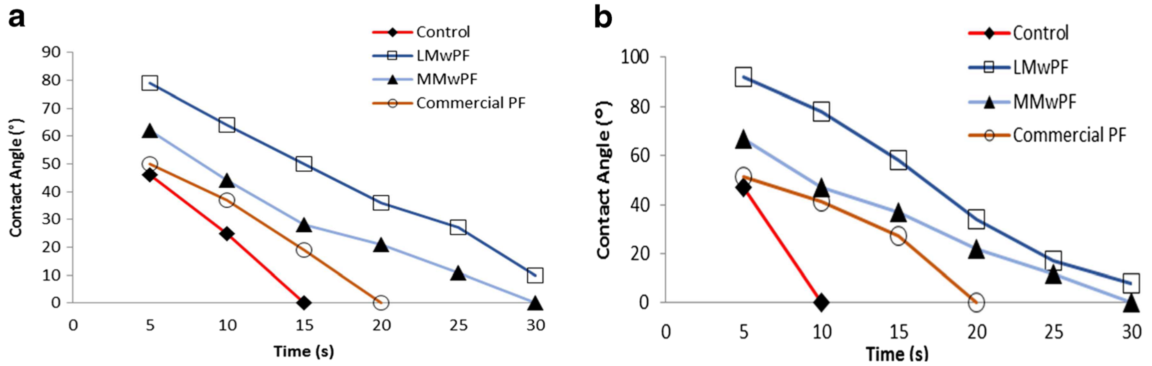


Fig. 7 Contact angle of distilled water on **a** outer and **b** inner sections of OPT veneer as a function of time (source: Nor Hafizah et al. [101])

(0.66, 1.59, and 1.18 mm, respectively), is comparable to that of boards made from agro-fibers. A similar result has been observed in bamboo. Although bamboo has excellent fiber properties compared with other nonwood fibers, when it is converted into MDF, the results are reversed. Because the amount of resin used in bamboo is low, increasing the amount of resin might improve the board's performance significantly. Zaidon et al. [109] reported similar results in using bamboo for hardboard. Their results revealed that optimum-quality mechanical bamboo pulps for hardboard production may be obtained by pretreating the chips by soaking them in 2 % NaOH for 6 h and then refining them in two cycles (first with 2.5-mm and second with 0.5-mm plate gaps). Apparently, MDFs made from bagasse and wheat straw also require a higher resin content to achieve superior board properties.

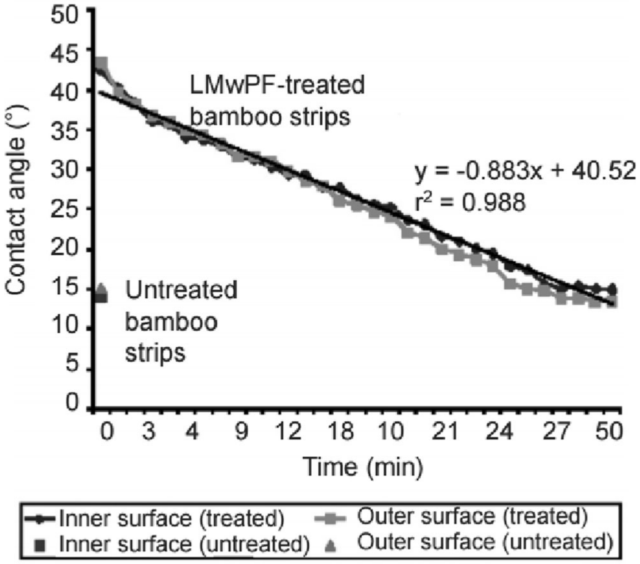


Fig. 8 Contact angle vs. time (min) of phenolic-treated and untreated bamboo strips (source: Anwar et al. [96]). Low molecular weight phenol formaldehyde (LMwPF)

Particleboard

Table 5 lists the mechanical and physical properties of particleboard made from various types of fibers. Generally, particleboard made from nonwood material has relatively poorer properties than that made from rubberwood, the main wood species used in particleboard and MDF plants in Southeast Asia. The best nonwood particleboards are made from hemp, OPT, bagasse, and canola straw. As with MDF, particleboard made from kenaf bast has significantly lower MOR and MOE values than panels made from kenaf core alone. Interestingly, the strength increases markedly when whole kenaf stem is used.

It has been observed that OPT board tends to have greater thickness swelling and water absorption than boards from other nonwoods, including EFBs and oil palm fronds. This condition may be a result of the parenchyma tissues in the trunk, which behave like a sponge and tend to absorb water easily. The parenchyma also has some advantages with regard to IB. Hashim et al. [114] produced much stronger particleboard from OPT without using a synthetic binder. In this case, they used a higher temperature and a longer pressing time to plasticize both the lignin and sugars (in the parenchyma tissues) to create natural binders, resulting in high MOR and IB strengths.

Most bast and straw fibers have low bonding strength due to the waxy cuticle layer on the outside of the fibers, which is responsible for their low wettability. According to Freytag and Donze [120], a small amount of residual wax may form a thin film on the fiber surface when heated above 60–70 °C, thus obstructing the penetration of aqueous solutions. This in turn leads to low resin penetration into the cell walls and lumens, reducing the number of links formed between the cells and the

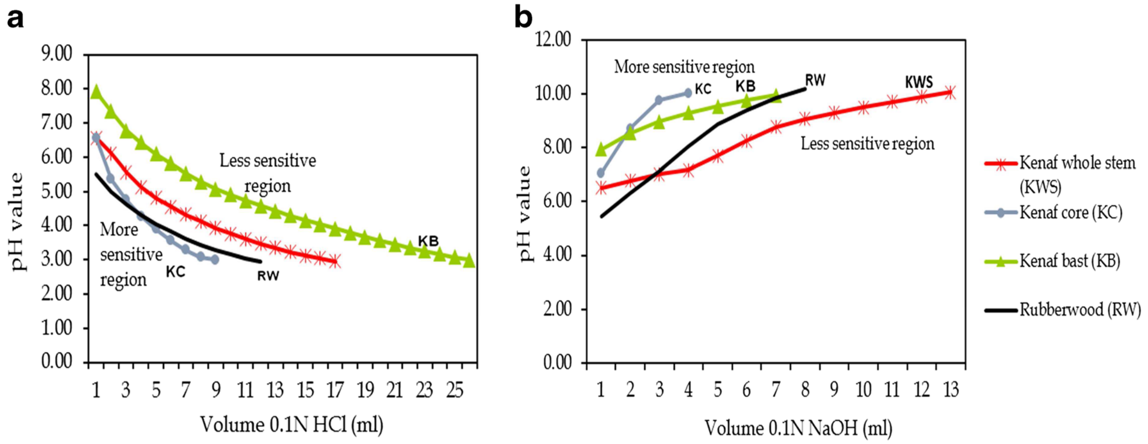


Fig. 9 Comparative stability of different parts of kenaf stem and rubberwood in **a** acidic and **b** alkaline solutions (source: Juliana et al. [29])

adhesive. These effects are more prominent in particleboards than in MDF; in the latter, most of the waxy layer is dissolved during the pulping process.

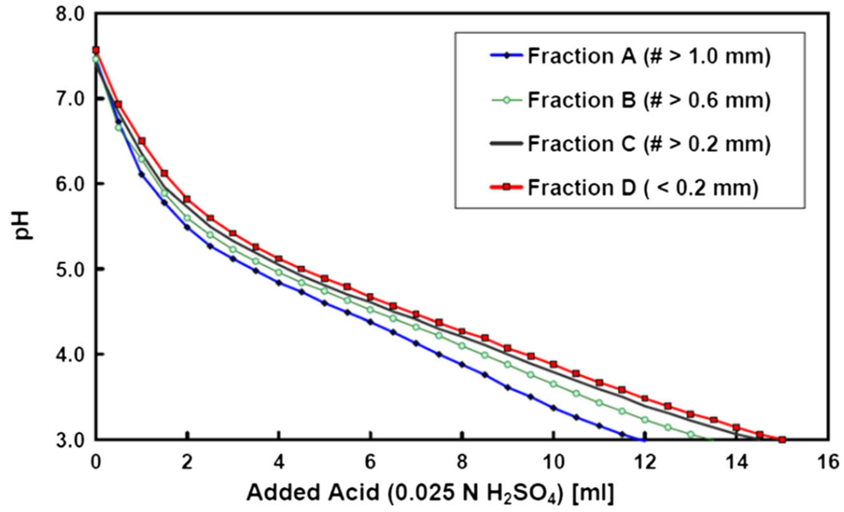
Veneer-Based and Laminated Products

Studies on plywood and laminated panels using bamboo and OPT were reported by Anwar et al. [121], Sulastiningsih et al. [122], Loh et al. [42•], Rahman et al. [123], and Srivaro et al. [124]. As shown in Table 6, both plywood and laminated products from OPT and bamboo have much higher strength and stiffness compared with particleboard and MDF. Laminated bamboo board exhibits much better performance than any of the fiber types, including wood products.

In plywood manufacturing, fiber properties (density and fiber length) play an important role in producing a high-quality product [128]. A previous study by Bhat et al. [129] revealed that bamboo has high elasticity and strength, making it suitable for the construction industry. For instance, bamboo, with high density (0.8–1.4 g/cm^3) compared with OPT (0.27–0.44 g/cm^3), has MOR, MOE, and shear values quite similar to those of commercial tropical hardwood plywood [42•, 121]. According to Loh et al. [42•], OPT has two regions within the trunk's diameter: an outer and an inner section. The outer section represents a much denser and stronger material compared with the inner section. As seen in Table 6, plywood made from only the inner part of OPT is inferior, even with an increased adhesive spread rate. Because of this variation in density, OPT veneers must be segregated into density classes to improve the strength and bond integrity of OPT plywood [42•]. In this study, arranging the low-density veneer in the core significantly increased the MOR and MOE values.

As shown in Table 6, laminated boards from bamboo are superior to those made from wood and OPT. A unidirectional laminated bamboo (ULB) board has higher strength, stiffness, and shear than a cross-laminated bamboo (CLB) board. [126] Notably, OPT performs quite well

Fig. 10 Buffering capacity of wheat straw toward acid (source: Halvarsson et al. [102])



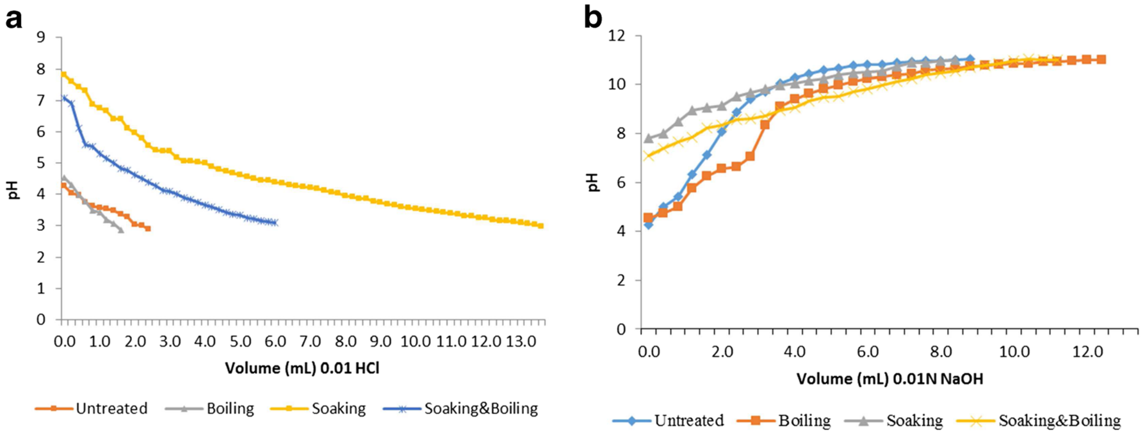


Fig. 11 Comparative stability of different EFB fiber treatments under **a** acidic and **b** alkaline solutions (source: Norul Izani et al. [94])

compared with other light wood species; thus, it may be of future importance because it is available throughout the year as plant biomass.

Issues and Challenges

Generally, most nonwood fiber composites have three issues that must be addressed: a consistent supply, adhesion, and dimensional stability. A sustainable and consistent supply of raw materials remains the most crucial factor in determining the survival of the nonwood composite industry. In the Asia–Pacific region, only a few commercial plants are seriously looking at using nonwood as a raw fiber material, despite the large number of studies being conducted. As for the issues of adhesion and dimensional stability, some commercial sectors have come up with several innovative solutions, including the use of new additives, nanoparticles for increasing dimensional stability, and high-quality preparation methods to enable more reproducible properties and better processing control. An increased understanding of the influence of factors such as moisture, fiber type, and fiber content has improved the mechanical properties of composites as well as the quality of their end products.

Surface interaction between resin polymer and natural fibers is an area that requires more concerted efforts. Because nonwood fibers come from many different sources, they vary greatly; therefore, there is a need to characterize their properties, particularly the interface between fiber and matrix, to obtain crucial information on adhesion strength as well as the resulting product. This evaluation may be done through several techniques, such as the following:

- Micromechanical techniques

  – Single-fiber pull-out test
  – Fiber bundle pull-out test
  – Single-fiber fragmentation test
  – Microbond test

- Spectroscopic techniques

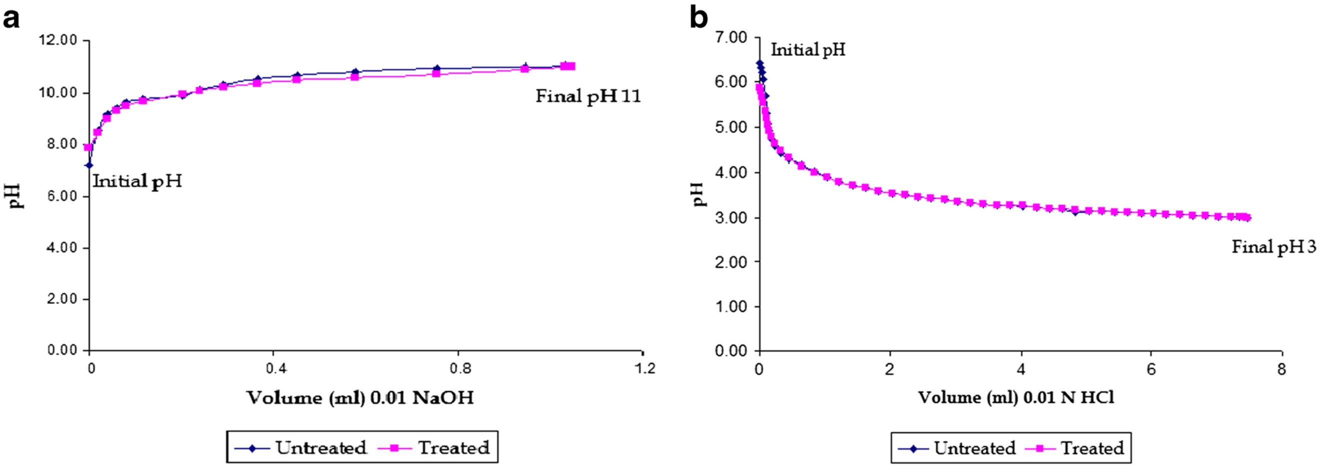


Fig. 12 Buffering capacity of bamboo strips in **a** acidic and **b** alkaline solutions (source: Anwar et al. [96])

Table 4 Properties of MDF manufactured from different types of nonwood fibers

Material	Resin type	Resin level (%)	Refining parameter (bar, min)	Board density (kg/m^3)	Pressing temp. (°C)	Press time (min)	Properties of Panel					Authors
							MOR (MPa)	MOE (MPa)	IB (MPa)	TS 24 h (%)	WA 24 h (%)	
Kenaf core	UF	12	7, 3	700	175	5	28.0	3379	0.67	15.4	68	Aisyah et al. [33]
			7, 5				30.3	3619	0.66	14.6	62	
Kenaf bast	UF	12	7, 3	700	175	5	20.6	1921	0.24	28.8	77.9	Aisyah et al. [37]
			7, 5				22.9	2113	0.17	27.1	73.9	
Oil palm trunk	UF	10	6, 1.7	720	200	5	38.3	3444	0.68	15.7	n/a	Zawawi et al. [104]
			6, 3.3				39.9	3538	0.72	14.6		
			6, 5.0				38.3	3597	0.73	14.6		
			6, 6.6				35.1	3421	0.73	14.4		
Oil palm frond	UF	9	6, 5	n/a	200	5	32.4	2870	1.12	14.3	n/a	Zawawi et al. [105]
Oil palm EFB	UF	11	n/a	700	170	5	21.0	1313	0.45	14.8	44.4	Harmaen et al. [106]
Bagasse	UF	20	n/a	900	125	60	45.0	3532	n/a	16.9	64.8	Das et al. [107]
Wheat straw	UF	6	n/a	750	138	7	17–18	2800–3000	03–0.4	34–35	n/a	Ye et al. [108]
		9					22–13	3200–3400	0.5–0.6	33–34		
		12					23–14	3200–3400	0.6–0.7	10–11		
Canola straw	UF	9	8, 8	700	170	4	19–20	1800–1900	0.50–0.52	32–35	–	Yousefi et al. [53]
		11				6	20–21	2000–2200	0.50–0.52	30–33		
						4	21–22	2300–2400	0.53–0.55	26–29		
						6	20–21	2200–2300	0.52–0.54	26–29		
Bamboo	UF	6	n/a	731	177	3.5	21.6	2190	0.70	37	105	Li et al. [57]
		7		730			23.6	2470	1.07	30	79	
		8		734			26.1	2760	1.16	25	72	
Rubberwood	UF	11	n/a	700	170	5	30.7	2412	0.5	16.5	46.3	Harmaen et al. [106]

UF urea formaldehyde, *MOR* modulus of rupture, *MOE* modulus of elasticity, *IB* internal bonding, *TS* thickness swelling, *WA* water absorption

Table 5 Properties of particleboard manufactured from different types of nonwood fibers

Material	Resin type	Resin level (%)	Board density (kg/m^3)	Pressing temp. (°C)	Press time (min)	Properties of panel					Authors
						MOR (MPa)	MOE (MPa)	IB (MPa)	TS 24 h (%)	WA 24 h (%)	
Kenaf stem	UF	10-F	700	150	5	13.90	n/a	0.40	19.1	n/a	Kalaycioglu and Nemli [110]
		8-M		130	5	12.80		0.37	12.3		
				150	5	12.70		0.36	14.5		
				130	5	13.30		0.38	12.7		
				150	7	15.40		0.41 0.37	18.2		
					7	13.00		0.39	16.6		
					5	13.40		0.40	17.8		
					7	13.50		0.43	14.2		
					5	15.20		0.43	10.2		
					7	16.30			10.2		
Kenaf stem	UF	10	700	160	6	15.1	1559	0.51	28	77	Juliana et al. [111]
Kenaf core						11.5	1365	0.09	67	179	
Kenaf bast						2.3	400	0.02	68	197	
Hemp	UF	10-F 8-M	700	200	n/a	16–17	3400–3500	0.77–0.79	27–29	74–79	Nikvash et al. [112]
Flax	UF	13	750	200	6	11.72	n/a	0.09	62.9	n/a	Papadopoulos and Hague [113]
OPT (strand)	No resin	n/a	800	180	20	24.95	n/a	0.93	41.6	80–85	Hashim et al. [114]
OPT (Fine)						4.04		0.49	43.6	104–109	
Oil palm frond	UF	8	700	160	6	10.83	890	0.57	23	92	Saiful Azry et al. [115]
		10				6.89	639	0.56	28	99	
		12				12.03	1049	0.62	19	83	
Oil palm EFB	MUF	11	650	160	6	21.99	1276	0.80	11.3	75	Zaidon et al. [116]
Bagasse	UF	10-F 8-M	700	200	n/a	17–18	3100–3200	0.42–0.44	25–27	61–66	Nikvash et al. [112]
Wheat straw	UF	5–17	700	200	2	3.0	660	0.02	240	n/a	Boquillon et al. [117]
Canola straw	UF	10-F 8-M	700	200	n/a	12–13	3100–3200	0.12–0.14	82–84	110–115	Nikvash et al. [112]
Rice husk	UF	8	650	180	8	4.69	176	0.04	49	67	Melo et al. [118]
Sunflower stalk	UF	11-F 9-M	700	150	7	15.65	1800.2	0.46	25.05	82.22	Bektas et al. [119]
Bamboo	UF	8	650	180	8	11.25	1343	0.22	30	72	Melo et al. [118]
Rubberwood	UF	10	700	160	6	19.6	2712	1.52	33	70	Juliana et al. [111]

OPT oil palm trunk, *UF* urea formaldehyde, *MUF* melamine urea formaldehyde, *MOR* modulus of rupture, *MOE* modulus of elasticity, *IB* internal bonding, *TS* thickness swelling, *WA* water absorption, *F* face, *M* middle, *n/a* not available

  - Surface characterization of the fiber (before and after treatment)

- Microscopic techniques

  - SEM
  - Optical microscopy
  - Stereomicroscopy

- Contact angle measurement
- Wettability
- Surface energy

Future Directions

Large amounts of nonwoods are readily available in the form of plantation crops, biomass, and forest products. These fiber resources differ significantly from one another; thus, specific harvesting and collection systems are needed to ensure a consistent supply of each raw material. Once such systems are established, there is no limit to the use of these fibers as raw materials in manufacturing particleboard, MDF, plywood, and laminated board. Kenaf core, OPT, bagasse, and straws (from wheat, rice, and oats) have promising properties for MDF production, whereas hemp, bagasse, OPT, and canola straw are more suitable for particleboard manufacture. In laminated products, the mechanical and physical properties of bamboo are far superior to those of panels made from wood species. OPT may be an important fiber resource in the future because of its sustainability and availability. All these new fiber resources demonstrate certain advantages over conventional composites, with some having greater mechanical properties.

Table 6 The properties of panel (laminated-based panel)

Board type	Material	Variable	Resin type	Glue spread (g/m^2)	Pressing temp. (°C)	Press time (min)	Pressure (MPa)	Properties of panel						Authors
								MOR (MPa)	MOE (MPa)	Shear (MPa)		CS (MPa)	TS (%)	
										Dry	Wet			
Plywood	Bamboo	30 AT 50 AT	PF	230–240	140	n/a	1.4	n/a	n/a	3.1 3.1	1.5 0.9	n/a	n/a	Anwar et al. [121]
	Bamboo (mat plywood)	n/a	UF	300	115	15	9	38.58	6176	n/a	n/a	n/a	2.3	Rahman et al. [123]
	OPT	100 % outer 100 % inner	UF	350	130	8	n/a	32.4 22.0	4020 2377	1.20 0.74	n/a	n/a	n/a	Loh et al. [42•]
Laminated veneer lumber	OPT	‖	PVAc	250 500	Ambient	30 60	10.8	n/a	n/a	4.80 4.99	n/a	n/a	<7 <7	Hashim et al. [125]
	Rubberwood	‖	PVAc	250 500	Ambient	30 60	10.8	n/a	n/a	4.75 6.01	n/a	n/a	<2 <2	Hashim et al. [125]
Laminated product	Bamboo ‖ (unidirectional laminated bamboo board)	*Gigantochloa apus* Three-layer Five-layer *Grevillea robusta* Three-layer Five-layer	TRF	170	Ambient	240	C	95.06 45.35 87.80 38.61	10,031 9490 9809 7267	4.0 5.5	n/a n/a	55 51 56 49	n/a	Sulastiningsih et al. [122]
		Heterocycla pubescens *Yunnanicus Hsueh*	PF	n/a	140	1.5	5	174.70 210.23	13,680 23,480	n/a	n/a	85 89	2.4 3.5	Wang and Guo [126]
	Bamboo ⊥ (cross-laminated bamboo board)	*H. pubescens* *Y. Hsueh*	PF	n/a	140	1.5	5	135.78 194.96	10,500 19,720	n/a	n/a	72 82	2.5 3.6	Wang and Guo [126]
	Rubberwood-oil palm sandwiched board Note: OPT as core, rubberwood as face	‖ ⊥	MUF	150 250 350 150 250 350	160	5	2	48 51 52 52 51 52	7609 7732 8458 7276 6979 6538	n/a	n/a	n/a	3.8 3.7 4.6 2.3 1.9 2.1	Srivaro et al. [124]
	Blockboard	Ekaba and fir wood Three-layer	PF	180	130	12	6.5	37.49	2766	n/a	n/a	n/a		Laufenberg et al. [127]

OPT oil palm trunk, *AT* assembly time, *C* clamp, *PF* phenol formaldehyde, *UF* urea formaldehyde, *MUF* melamine urea formaldehyde, *TRF* tannin resorcinol formaldehyde, *PVAc* polyvinyl acetate, *MOR* modulus of rupture, *MOE* modulus of elasticity, *CS* compression strength, *TS* thickness swelling, ‖ parallel to the grain direction, ⊥ perpendicular to the grain direction, *n/a* not available

Compliance with Ethics Guidelines

Conflict of Interest The authors of this paper declare that they have no conflicts of interest

Human and Animal Rights and Informed Consent This article contains no studies with human or animal subjects performed by the author.

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