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Review

Kenaf fiber reinforced composites: A review

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ABSTRACT

The development of high-performance engineering products made from natural resources is increasing worldwide, due to renewable and environmental issues. Among the many different types of natural resources, kenaf plants have been extensively exploited over the past few years. Therefore, this paper presents an overview of the developments made in the area of kenaf fiber reinforced composites, in terms of their market, manufacturing methods, and overall properties. Several critical issues and suggestions for future work are discussed, which underscore the roles of material scientists and manufacturing engineers, for the bright future of this new "green" material through value addition to enhance its use.

1. Introduction

Fiber crops have existed in human society since the beginning of time. History shows that humans collected raw materials from the wild to use as ropes or textiles. Later, societies learned to cultivate such crops. Natural fiber crops are among the earliest known cultivated plants and humans have continued to domesticate these crops over time. Fiber crop varieties have been extensively developed through breeding and selection according to societies' needs and values [1]. The worldwide availability of natural fibers and other abundantly accessible agro-waste is responsible for this new polymer science and engineering research, and the search for a sustainable technology. Natural fibers were introduced with the intention of yielding lighter composites, coupled with lower costs compared to existing fiber glass reinforced polymer composites. Natural fibers have a lower density (1.2–1.6 g/cm^3) than that of glass fiber (2.4 g/cm^3), which ensures the production of lighter composites [2]. Conventional petroleum based plastics, such as polypropylene and polyethylene, are used extensively with natural fibers, such as hemp, jute, sisal, and kenaf [3].

Recently, the rapidly expanding use of composite components in automotive, construction, sports and leisure, and other mass production industries, has been focused on sustainable and renewable reinforced composites [4]. This interest encompasses a wide variety of shapes and materials ranging from synthetic to natural, in order to fulfill the demands of producing composites with desired properties. The incorporation of reinforcements, such as fibers and fillers into composites affords a means of extending and improving the properties of the composites that meets the requirements of most engineering applications. Consequently, these improvements will be associated with economic advantages, such as low production costs and low resin consumption [1]. As a result, the demands for natural fiber reinforced composites have increased drastically over the past few years, for various commercial applications in the industrial sector.

In this scientific review article, the overall characteristics of kenaf fiber reinforced composites, in terms of mechanical properties, thermal properties, as well as water absorption properties, will be reviewed. Moreover, the manufacturing processes will be discussed, and the key technical issues that need to be solved in the future, will also be addressed. Whilst review articles and even books on the overall properties of natural fiber reinforced composites have been published [3,5], the authors have concluded that a specific review article on the overall characteristics of kenaf fiber reinforced composites, has not yet been published; it is believed that such an article should be of significant value to the composite research community.

2. Natural fiber composites

Over the past few decades, there has been a growing interest in the use of natural fibers in composite applications. These types of composites present many advantages compared to synthetic fibers, such as low tool wear [6], low density, cheaper cost, availability, and biodegradability [7]. The most common natural plant used in applications are bast fibers, such as hemp, jute, flax, kenaf, and sisal [8]. One of the reasons for this growing interest is that natural fibers have a higher specific strength than glass fiber and a similar specific modulus [3]. With these properties and cheaper sources, these natural fibers theoretically offer desirable specific strengths and modulus, at a lower cost [2]. These natural fibers, found in all life cycles of all walks of life, are shown in Fig. 1. Many naturally occurring fibers can be used as composites, but mostly in

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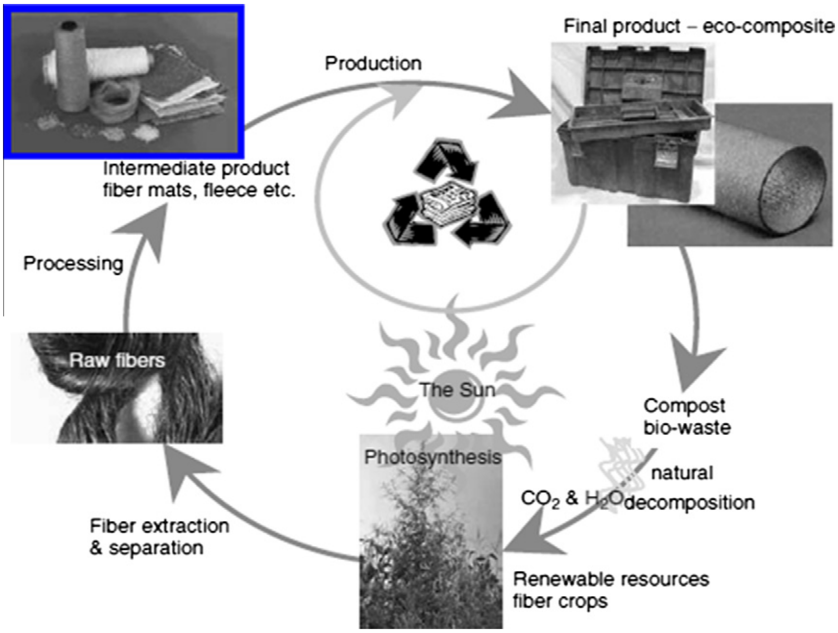


Fig. 1. Life cycle of bio-composites.

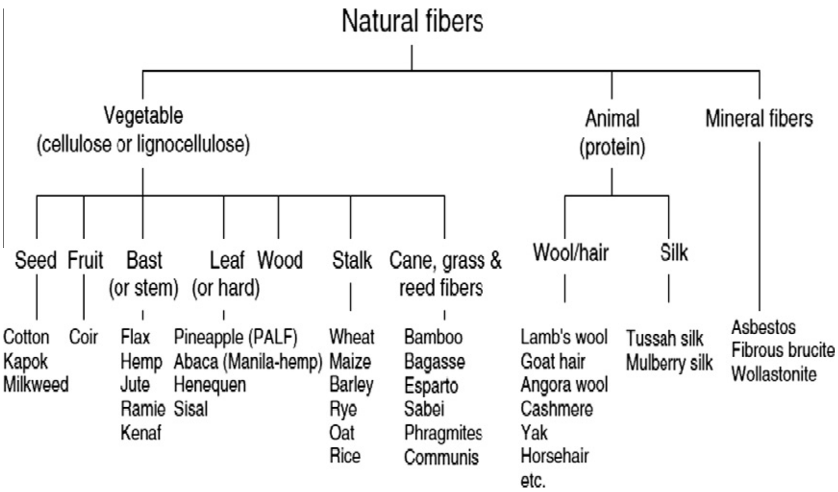


Fig. 2. Classification of natural fibers.

applications that involve low stress. Some of the fibers are obtained by processing agricultural, industrial, or consumer waste [9]. These materials have already been embraced by European car makers and this trend has reached North America and the Natural Fibers Composites Industry has registered a 40–50% growth during the year 2000 [10].

2.1. Natural (plant) fibers

Natural fibers are subdivided based on their origins i.e., whether they are derived from plants, animals, or minerals, as shown in Fig. 2. According to study groups, plant fibers are the most popular of the natural fibers, used as reinforcement in fiber reinforced composites. Plant fibers include bast (or stem, soft, or sclerenchyma) fibers, leaf or hard fibers, seed, fruit, wood, cereal straw, and other grass fibers. The chemical composition, as well as the structure of plant fibers, is fairly complicated (as illustrated in Table 1). Plant fibers are composite materials designed by nature. The fibers are basically comprised of a rigid, crystalline cellulose microfibril reinforced amorphous lignin, and/or hemicelluloses matrix. Most plant fibers, except for cotton, are composed of cellulose, hemicelluloses, lignin, waxes, and several water-soluble compounds; where cellulose, hemicelluloses, and lignin are the major constituents.

The main constituent of any plant fiber is cellulose [11]. Cellulose is the natural homopolymer (polysaccharides), where D-glucopyranose rings are connected to each other with β-$(1 \rightarrow 4)$-glycosidic linkages, as can be seen in Fig. 3. Cellulose is often found as a relatively high modulus, fibril component, of many naturally occurring composites, such as wood; where it is found in association with lignin. In a previous study by Chawla [11], most of plant fibers contained 65–70% cellulose, which is composed of three elements, C, H, and O_2, with a general formula of $C_6H_{10}O_5$, which are crystalline. The lignin and other non-cellulosic substances are associates with the cell walls and their presence modifies the final properties of the fiber. The non-cellulose material is hardly ever completely removed from these fibers, mainly because it is

Table 1
Chemical composition, moisture content and microfibrillar angle of plant fibers [5].

Fibers	Cellulose (%)	Hemicellulose (%)	Lignin (wt.%)	Pectin (wt.%)	Moisture content (wt.%)	Waxes (%)	Micro-fibrillar angle (°)
Flax	71	18.6–20.6	2.2	2.3	8–12	1.7	5–10
Hemp	70–74	17.9–22.4	3.7–5.7	0.9	6.2–12	0.8	2–6.2
Jute	61–71.5	13.6–20.4	12–13	0.2	12.5–13.7	0.5	8
Kenaf	45–57	21.5	8–13	3–5			
Ramie	68.6–76.2	13.1–16.7	0.6–0.7	1.9	7.5–17	0.3	7.5
Nettle	86				11–17		
Sisal	66–78	10–14	10–14	10	10–22	2	10–22
Henequen	77.6	4–8	13.1				
PALF	70–82		5–12.7		11.8		14
Banana	63–64	10	5		10–12		
Abaca	56–63		12–131	1	5–10		
Oil palm EFB	65		19				42
Oil palm mesocarp	60		11				46
Cotton	85–90	5.7		0–1	7.85–8.5	0.6	–
Coir	32–43	0.15–0.25	40–45	3–4	8		30–49
Cereal straw	38–45	15–31	12–20	8			

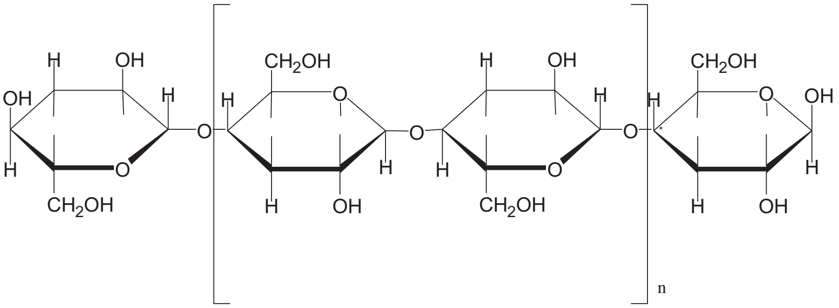


Fig. 3. Chemical structure of cellulose.

prohibitively expensive to do so. An important attribute of plant fibers is their ability to absorb moisture from the atmosphere in comparatively large quantities [11], because cellulose is hygroscopic. Most polymeric fibers swell due to moisture absorption. This absorption leads to alterations in weights and dimensions, as well as in strengths and stiffness. In addition, plant fiber is exposed to biological decay. Most plant fibers darken and weaken with age and exposure to light. Plant fibers are not as durable as synthetic polymeric fibers. They are all easily attacked by a variety of organisms, at high humidity and temperature, leading to rot and mildew. Therefore, plant fibers are considered as renewable resources and they do not exacerbate the CO_2 emissions problem.

2.2. Properties and characteristics of natural (plant) fibers

Table 2 summarizes characteristic values for the density, diameter, and mechanical properties, of natural (plant) and synthetic fibers [5]. Natural (plant) fibers are non-abrasive towards mixing and molding equipment, which can contribute to significant equipment maintenance cost reductions. They also present safer handling and working conditions compared to synthetic reinforcements, such as glass fibers. Their processing is environmental friendly, offering better working conditions and therefore, a reduction in risk of dermal or respiratory problems. The most interesting aspect of natural (plant) fibers is their positive environmental impact. Natural (plant) fibers are renewable resources, where they are biodegradable and their production requires little energy [12]. A major drawback of natural (plant) fibers compared to synthetic fibers is their non-uniformity, variety of dimensions, and their mechanical properties (even between individual natural (plant) fibers in the same cultivation) [5]. Therefore, the major task to be solved, in order to boost the acceptance of natural (plant) fibers as a quality alternative to conventional reinforcing fibers, is to develop high performance natural fiber reinforced composites [13,14].

Natural (plant) fibers generally contain large amounts of the hydroxyl group, which makes them polar and hydrophilic in nature. However, most plastics are hydrophobic in nature. The addition of hydrophilic natural (plant) fibers to hydrophobic plastic will result in a composite with poor mechanical properties due to non-uniform fiber dispersion in the matrix, and an inferior fiber matrix interphase [15]. This polar nature also results in high moisture sorption in natural (plant) fiber based composites, leading to fiber swelling and voids in the fiber matrix interphase. Moisture, if not removed from natural (plant) fibers prior to compounding by drying, will result in a porous product. High moisture absorption could also cause a deterioration in mechanical properties and loss of dimensional stability [16,17]. These problems are generally solved by fiber surface treatment or matrix modifications [16–18]. Another major limitation, in exploiting the use of natural (plant) fibers, is the limited thermal stability possessed by natural (plant) fibers. They undergo degradation when processed beyond 200 °C; this further limits the choice of plastic materials to be used as matrix [5,19].

2.3. Kenaf fibers

Kenaf is one of the natural (plant) fibers used as reinforcement in Polymer Matrix Composites (PMCs). Kenaf (*Hibiscus cannabinus*, L. family Malvacea) has been found to be an important source of fiber for composites, and other industrial applications (Fig. 4) [20]. Kenaf is well known as a cellulosic source with both economic

Table 2
Characteristic values for the density, diameter, and mechanical properties of (natural) plant and synthetic fibers [10].

Fibers	Density (g cm^3)	Diameter (μm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Flax	1.5	40–600	345–1500	27.6	2.7–3.2
Hemp	1.47	25–500	690	70	1.6
Jute	1.3–1.49	25–200	393–800	13–26.5	1.16–1.5
Kenaf			930	53	1.6
Ramie	1.55		400–938	61.4–128	1.2–3.8
Nettle			650	38	1.7
Sisal	1.45	50–200	468–700	9.4–22	3–7
Henequen					
PALF		20–80	413–1627	34.5–82.5	1.6
Abaca			430–760		
Oil palm EFB	0.7–1.55	150–500	248	3.2	25
Oil palm mesocarp			80	0.5	17
Cotton	1.5–1.6	12–38	287–800	5.5–12.6	7–8
Coir	1.15–1.46	100–460	131–220	4–6	15–40
E-glass	2.55	<17	3400	73	2.5
Kevlar	1.44		3000	60	2.5–3.7
Carbon	1.78	5–7	3400[a]–4800[b]	240[b]–425[a]	1.4–1.8

[a] Ultra high modulus carbon fibers.
[b] Ultra high tenacity carbon fibers.

Fig. 4. Kenaf plants.

and ecological advantages; in 3 month (after sowing the seeds), it is able to grow under a wide range of weather conditions, to a height of more than 3 m and a base diameter of 3–5 cm [21]. This statement is supported by previous studies, which mentions that growing speed may reach 10 cm/day under optimum ambient conditions [14]. Kenaf was priced at $400 per tonne in 1995 and from $278 to $302 per tonne in 2000. From the viewpoint of energy consumption, it takes 15 MJ of energy to produce 1 kg of kenaf; whereas it takes 54 MJ to produce 1 kg of glass fiber [14]. The kenaf plant is composed of many useful components (e.g., stalks, leaves, and seeds) and within each of these there are various usable portions (e.g., fibers and fiber strands, proteins, oils, and allelopathic chemicals) [22]. The yield and composition of these plant components can be affected by many factors, including cultivar, planting date, photosensitivity, length of growing season, plant populations, and plant maturity [23]. Kenaf filaments consist of discrete individual fibers, of generally 2–6 mm. Filaments and individual fiber properties can vary depending on sources, age, separating technique, and history of the fibers. The stem is straight and unbranched and is composed of an outer layer (bark) and a core [24]. It is easy to separate the stem into bark and core, either by chemicals and/or by enzymatic retting. The bark constitutes 30–40% of the stem dry weight and shows a rather dense structure. On the other hand, the core is wood-like and makes up the remaining 60–70% of the stem [25]. The core reveals an isotropic and almost amorphous pattern. However, the bark shows an orientated high crystalline fiber pattern.

The schematic representation of the natural plant cell wall is shown in Fig. 5. This structure is often called the microfibril, microfiber, or primary/elementary fiber [10]. The microfibril size and chemical content of the kenaf stem, is shown in Table 3. On average, natural fibers, including kenaf fibers, contain 60–80% cellulose, 5–20% lignin (pectin), and up to 20% moisture [23,26–28]. The cell wall consists of a hollow tube with four different layers; one primary cell wall, three secondary cell walls, and a lumen; which is an open channel in the center of the microfibril. Each layer is composed of cellulose embedded in a matrix of hemicellulose and lignin; a structure that is analogous of artificial fiber reinforced composites. Hemicellulose is made up of highly branched polysaccharides, including glucose, mannose, galactose, xylose, and others [26]. Lignin is made up of aliphatic and aromatic hydrocarbon polymers positioned around fibers. The structure and contents of

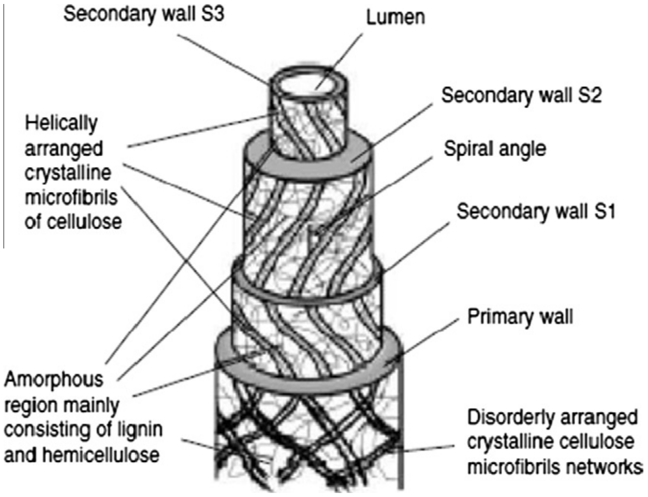


Fig. 5. Schematic picture of cell wall of the natural plans [10].

Table 3
Macrofibril size and chemical content of kenaf stem [6].

	Bark	Core
Fibril length, *L* (mm)	2.22	0.75
Fibril width, *W* (μm)	17.34	19.23
L/*W*	128	39
Lumen diameter (μm)	7.5	32
Cell wall thickness (μm)	3.6	1.5
Cellulose (%)	69.2	32.1
Lignin (%)	2.8	25.21
Hemicellulose (%)	27.2	41
Ash content (%)	0.8	1.8

the cell wall differs widely between different species and between different parts of the plants. Scientists state that the overall properties of kenaf fiber depends on the individual properties of each of its components [10]. The strength and stiffness of the fibers are provided by cellulose components via hydrogen bonds and other linkages. Hemicellulose is responsible for biodegradation, moisture absorption, and thermal degradation of the fibers. On the other hand, lignin (pectin) is thermally stable, but responsible for the UV degradation of the fibers.

The primary (outer) cell wall is usually very thin (<1 μm), but the secondary cell wall is composed of three layers. Of these, the secondary layer is the thickest and is the major contributor (at 80%) to the overall properties. The secondary layer is formed by microfibrils, which contain larger quantities of cellulose molecules. The microfibrils run fairly parallel to each other and follow a steep helix around the cell. Furthermore, the microfibril is composed of alternating crystalline and amorphous regions; the crystallite size is approximately 5–30 nm in a lateral direction and between 20 and 60 nm along the axis. Therefore, the cellulose molecules pass through several crystallites along the axis. This is called a fringed micelle structure.

A previous reviewer indicated that kenaf has been actively cultivated in recent years for two main reasons [10]. One is that kenaf absorbs nitrogen and phosphorus that is present in the soil. The average absorption rate for kenaf is 0.81 g/m^2 per day for nitrogen and 0.11 g/m^2 per day for phosphorus; these rates are several times higher than those with a variety of stress. The other reason is that kenaf accumulates carbon dioxide at a significantly high rate. The photosynthesis rate of kenaf is much higher than photosynthesis rates of conventional trees [7,14]. To make kenaf a successful alternative crop, it must be incorporated into value-added products. People have skilfully made use of kenaf from ancient times, traditionally as ropes, canvas, sacking, and more recently, kenaf has been used as an alternative raw material in place of wood used in pulp and paper industries to avoid the destruction of forests. It has also been used to make non-woven mats in the automotive industry and textiles [29]. About 35% of kenaf is bast fiber, which is suitable for paper, textiles, and rope; and about 65% is core [25].

Table 4
Properties of filled/reinforced polypropylene composites [30].

Filler/reinforcement in PP	Units	Neat PP	Kenaf	Glass	Talc	Mica
Filler by weight	%	0	50	40	40	40
Filler by volume	%	0	39	19	18	18
Specific gravity	–	0.9	10.7	1.23	1.27	1.26
Tensile modulus	GPa	1.7	8.3	9	4	7.6
Specific tensile modulus	GPa	1.9	7.8	7.3	3.1	6.0
Tensile strength	MPa	33	65	110	35	39
Specific tensile strength	MPa	37	61	89	28	31
Flexural modulus	GPa	1.4	7.3	6.2	4.3	6.9
Specific flexural modulus	GPa	1.6	6.8	5.0	3.4	5.5
Elongation at break	%	≫10	2.2	2.5	–	2.3
Notched Izod impact	J/m	24	32	107	32	27
Water absorption (24 h)	%	0.02	1.05	0.06	0.02	0.03

Kenaf is presently being used in paper production on a very limited basis. Various uses of the bast fibers have been explored, such as in the making of industrial socks to absorb oil spills, as well as making woven and non-woven textiles. The kenaf bast fiber is known to have the potential as a reinforcing fiber in thermoplastic composites, because of its superior toughness and high aspect ratio in comparison to other fibers. A single fiber of kenaf can have a tensile strength and modulus as high as 11.9 GPa and 60 GPa, respectively [20]. Rowell et al. [30] studied the potential of kenaf as a reinforcing fiber in a polypropylene matrix and compared the mechanical properties with other commonly used composite systems. The results are shown in Table 4. Kenaf core fibers are also used in product applications such as animal bedding, summer forage, and potting media [31].

2.4. Challenges for kenaf fiber (or filler) as a reinforcement in polymer composites

2.4.1. Interphase

The main disadvantage encountered during the addition of natural fibers, including kenaf fiber into a polymer matrix, is the lack of good interfacial adhesion between the two components, which results in poor properties in the final product [32–34]. Polar hydroxyl groups, on the surface of the kenaf fiber, have difficulty forming a well bonded interphase with a relative nonpolar matrix; as the hydrogen bonds of the fiber surface tend to prevent the wetting of the filler surface. Furthermore, the incorporation of kenaf fiber as a filler in a polymer matrix is often associated with agglomeration, as a result of insufficient dispersion caused by the tendency of fibers to form hydrogen bonds with each other [35,36]. Fiber–matrix interfacial adhesion can be improved with many chemical modifications of the fiber and one of the familiar and effective modifications applied to kenaf fiber, is an alkaline treatment based on sodium hydroxide (NaOH) [34,37].

2.4.2. Water absorption

Humidity aging is widely recognized as one of the main causes of long-term failure of an organic matrix exposed to the atmosphere; or in contact with an aqueous media. There are several recognized modes of humidity aging, namely plasticization of the matrix, differential swelling related to concentration gradients, embrittlement linked the degradation of the macromolecular skeleton by hydrolysis, osmotic cracking, hygrothermic shock with change of water state, and a damage localized matrix/fiber interface [38]. Additionally, humidity aging also causes undesirable effects to the mechanical properties and dimensional stability of composites. Therefore, it is important to study the water absorption behavior in order to estimate, not only the consequences that the absorbed water may cause, but also the durability of the natural fiber composites under water [39]. Generally, most researchers agree that moisture penetration into composite materials is conducted by three different mechanisms. The main mechanism consists of the diffusion of water molecules into the micro-gaps between polymer chains. The second mechanism involves capillary transport into the gaps and flaws, which interfaces between the fiber and the matrix due to incomplete wettability and impregnation. The third mechanism involves the transport of micro-cracks in the matrix, formed either during the compounding process, or due to fiber swelling [39,40]. Matrix such as polyester, are easily hydrolyzed by moisture, resulting in a molecular weight reduction [41,42]. The rate of this hydrolytic degradation is dependent on temperature and humidity [41]. This would lead to an extensive loss in mechanical properties of natural fiber based composites, especially kenaf fiber reinforced composites in a humid environment [42].

2.4.3. Chemical treatments

Chemical modification or treatment of the natural fibers, including kenaf, is generally carried out using reagents, which contain functional groups that are capable of bonding with the hydroxyl group from the natural fibers. Several types of chemical modifications have been reported in previous literatures, which include alkaline treatment, silane treatment, isocyanate treatment, and acetylation [43].

Alkaline treatment (or mercerization) is one of the most widely used chemical treatments for natural fibers, especially the kenaf fiber when reinforcing thermoplastics and thermosets [34,37,44,45]. This modification is carried out by immersing the fibers in a NaOH solution for a period of time [45–47]. The important modification that is done by alkaline treatment is the disruption of hydrogen bonding in the network structure, thereby increasing surface roughness. This treatment removes certain hemicelluloses, lignin, wax and oils covering the external surface of the fiber cell wall; depolymerizes cellulose, and exposes the short length crystallites. Alkaline treatment leads to fibrillation of the fiber bundles into small fibers. In other words, this treatment reduces fiber diameter and thereby increases aspect ratio. The addition of aqueous sodium hydroxide (NaOH) to the natural fiber promotes the ionization of the hydroxyl group to the alkoxide (Eq. (1)) [45,46].

$$\text{Fiber—OH} + \text{NaOH} \rightarrow \text{Fiber—ONa}^{+} + \text{H}_2\text{O} \qquad (1)$$

It is reported that alkaline treatment has two effects on the fiber: (1) it increases surface roughness, resulting in better mechanical interlocking; and (2) it increases the amount of cellulose exposed on the fiber surface, thus increasing the number of possible reaction sites. Consequently, alkaline treatment has a lasting effect on the mechanical behavior of natural fibers, especially on their strength and stiffness [43,45,46].

Silane is a chemical compound with the chemical formula of SiH_4. Silane is used as coupling agents to allow natural fiber to adhere to a polymer matrix, thus stabilizing the composite material. Silane coupling agents may reduce the number of cellulose hydroxyl groups in the fiber–matrix interface. In the presence of moisture, the hydrolysable alkoxy group leads to the formation of silanols. The silanol then reacts with the hydroxyl group of the fiber, forming stable covalent bonds to the cell wall that are chemisorbed onto the fiber surface. Therefore, the hydrocarbon chains (R), provided by the application of silane, restrain the swelling of the fibers by creating an entangled network due to the diffusion of hydrocarbon chains into the matrix [40]. The reaction schemes are given as:

$$\text{Fiber—OH} + \text{R—Si(OH)}_3 \rightarrow \text{Fiber—O—Si(OH)}_2\text{—R} \qquad (2)$$

It was assumed that the hydrocarbon chains produced by the silane application influenced the wettability of the fibers, thus improving the chemical affinity of the polymer matrix. Silane treatment also enhanced the tensile strength of the composites, minimized the effect of moisture on the composite's properties, increased adhesion, and thereby, the composites strength [43,45,46]. Silane treatment has been introduced to kenaf fiber by previous researchers over the past few years [44,48]. Magnificent results were recorded for treated composites, in terms of interfacial adhesion between kenaf filler and the polymer matrix.

The acetylation of plants is a well-known esterification method of introducing plasticization to cellulosic fibers. Acetylation has been extensively applied to wood cellulose to stabilize the cell wall, improving dimensional stability, and environmental degradation. Acetylation is based on the reaction of the cell wall hydroxyl groups of lignocellulosic materials, with acetic or propionic anhydride at an elevated temperature (usually without a catalyst) [40]. The reaction scheme is given as follows:

$$\text{Fiber—OH} + (\text{H}_3\text{C—CO})_2\text{O} \rightarrow \text{Fiber—O—CO—CH}_3 + \text{CH}_3\text{COOH} \qquad (3)$$

Acetic acid (a by-product from the reaction) must be removed before the fibers are used. The hydroxyl groups that react with the reagent are those of lignin and hemicelluloses (amorphous material), while the hydroxyl groups of cellulose (crystalline material), being closely packed with hydrogen bonds, prevent the diffusion of the reagent and thus result in very low extents of reaction. It has been shown that etherification improves the dispersion of fibers in a polymer matrix, as well as the dimensional stability and interface of the final composites [45,46].

2.5. Properties of kenaf fiber reinforced composites

2.5.1. Mechanical properties

The performance of materials is always presented in terms of their mechanical characteristics, such as tensile properties, flexural properties, compression properties, impact properties and wear behavior. These characteristics are important to determine material ability, especially under extreme and critical conditions, which are directly connected with engineering performance. For the past few years, numerous studies have been performed on kenaf fiber reinforced composite, in order to fully characterize its mechanical behavior [30,49–52]. Some of the mechanical properties of kenaf fiber reinforced composites determined, included: Ultimate tensile strength (the maximum engineering stress in tension that may be sustained without fracture, often known as tensile strength), fracture strain (stress at fracture from a bend or flexure test), flexural modulus (an indication of a material's stiffness when flexed, which is the ratio, within the elastic limit, of the applied stress on a test specimen in flexure, to the corresponding strain in the outermost fibers of the specimen), and impact strength (the degree of resistance of any material to impact loading, with or without a notch in it). Generally, the tensile and flexural properties of kenaf reinforced composites, vary depending on the type of fiber, its orientation (random or unidirectional), content and form (fiber or fabric), and the type of blending/plasticizer used. For example, Ochi [50] reported that the tensile and flexural strength of kenaf reinforced PLA composites, increase linearly with fiber contents up to 50%. Statically, the tensile and flexural strength of kenaf reinforced composites were approximately 223 MPa and 254 MPa, respectively, in samples with a fiber fraction of 70%. According to the

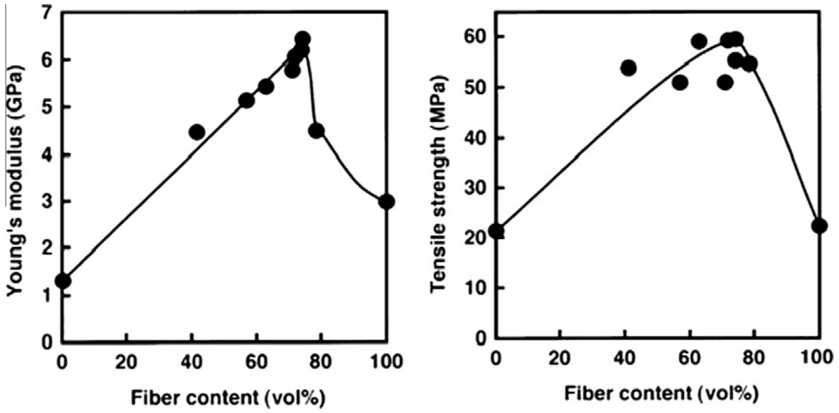


Fig. 6. Relationship between Young's modulus, the tensile strength, and the kenaf fiber content of kenaf/PLLA composite.

results obtained by this researcher, this proved that kenaf fiber exhibits higher strength values in terms of tensile and flexural properties, as compared to other natural fibers, when reinforcing PLA [7,53,54]. A more recent study of the fiber content on mechanical properties of kenaf fiber reinforced composite was carried out by Nishino et al. [7]. Generally, optimum tensile properties and Young's modulus are dictated by the volume of reinforcing fiber used for the composites. As can be seen in Fig. 6, both properties increased with the increase of fiber content and showed the maximum values (Young's modulus; 6.4 GPa, and the tensile strength; 60 MPa) around a fiber content of 70 vol.%. The decrease in the mechanical properties of the composite with the fiber content above 70 vol.% could be due to insufficient filling of the matrix resin. Meanwhile, Fig. 7 shows the stress–strain curves of the kenaf sheet, the PLLA film, and the kenaf/PLLA composite, with a fiber content of 70 vol.%. Young's modulus and tensile strength were higher for the composite compared with those of the matrix resin. These reveal that the incorporation of kenaf fibers into the matrix is quite effective for reinforcement. The mechanical properties of the composite were enhanced compared to those of the kenaf sheet itself. When the sheet was stretched using the tensile tester, the angular change of the kenaf fiber to the stretching direction was considered to be the main deformation mechanism for the sheet. This type of deformation will be restricted for the composite, because the matrix resin was impregnated into the interfibrillar regions. This is considered to be one reason for the reinforcement. Another reason is due to a good stress transfer from the matrix to the incorporated kenaf fibers.

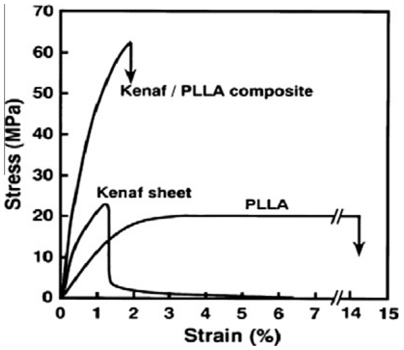


Fig. 7. Stress–strain curves of the kenaf sheet, the PLLA film and the kenaf/PLLA composite.

Fiber orientation is another decisive factor that has significant influence on the mechanical properties of kenaf fiber reinforced composites. Fig. 8 indicates the mechanical properties of the kenaf sheet, the PLLA film, and the kenaf/PLLA composite, in the directions both parallel and perpendicular to the preferential fiber orientation. As cast PLLA film was isotropic, the kenaf sheet showed large mechanical anisotropies. This anisotropy reflected on the mechanical properties of the composite, where the composite showed large anisotropies in the Young's modulus and tensile strength. On the other hand, incorporating specific additives into the polymer matrix could also improve the mechanical properties of kenaf fiber reinforced composite. As Rowell et al. [30] pointed out, the inherent polar and hydrophilic nature of the lignocellulosic fibers, and the non-polar characteristics of the polyolefins, resulted in difficulties in compounding/blending of the fibers and matrix.

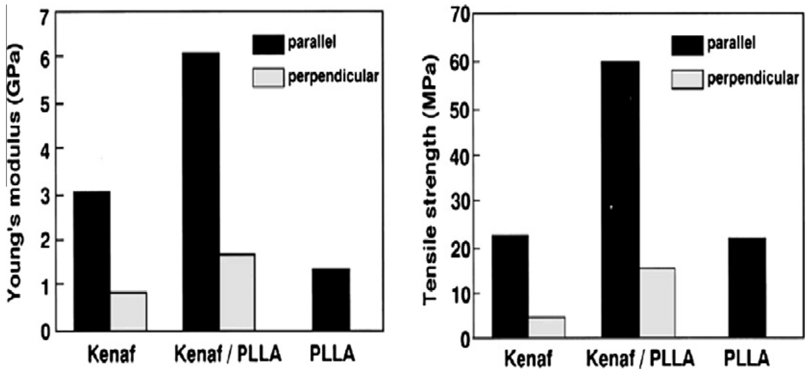


Fig. 8. Mechanical properties of Kenaf sheet, the PLLA film and the Kenaf/PLLA composite in the direction of both parallel and perpendicular to the preferential orientation direction of the fibers.

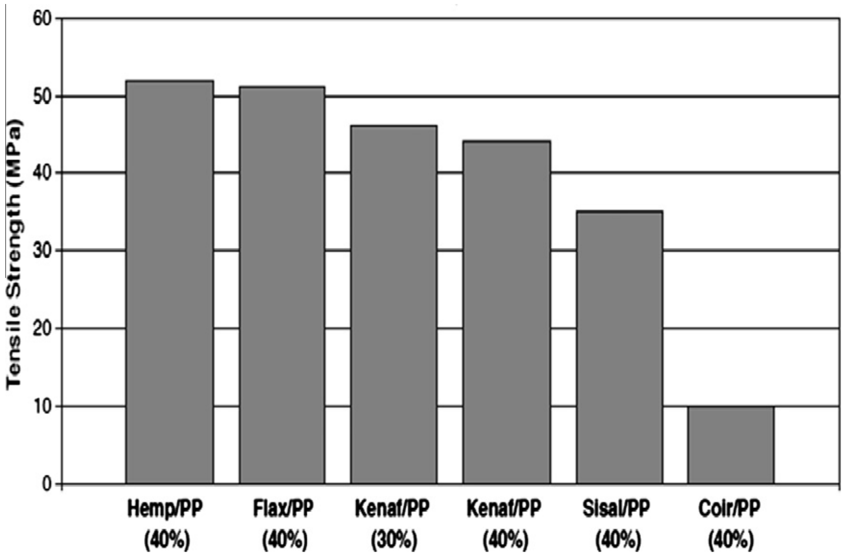


Fig. 9. Comparison of tensile strength of kenaf/PP–MAPP composites to other natural fiber composites.

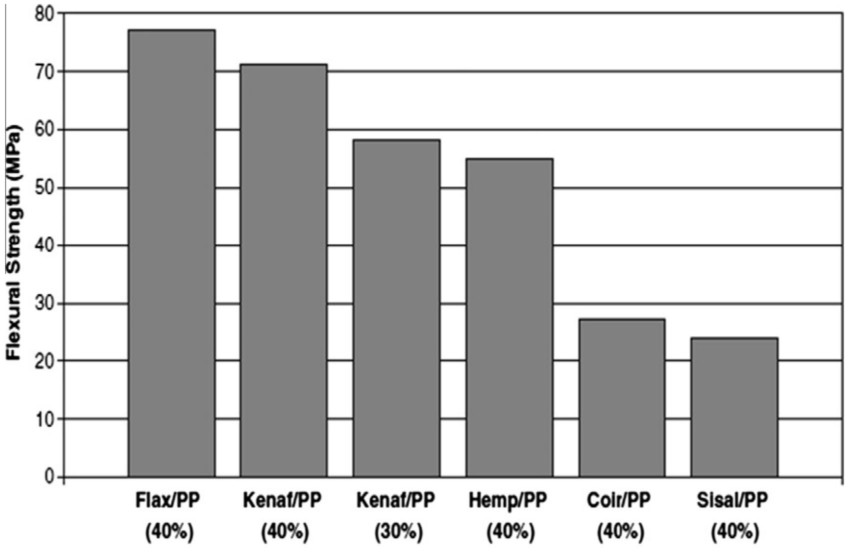


Fig. 10. Comparison of flexural strength of kenaf/PP–MAPP composites to other natural fiber composites.

Therefore, a specific coupling agent is needed in order to enhance the compatibility between filler and matrix, especially in a kenaf–PP system. Recently, Maleic Anhydride (MA) grafted Polypropylene (MAPP) has been widely used in kenaf–PP systems. Interestingly, Sanadi and his co-workers [29] reported a significant improvement in terms of tensile and flexural properties of kenaf–PP composite, when incorporating it with MAPP as a coupling agent. They found that coupled composites, showing a superior tensile strength of up to 74 MPa, were achieved with the higher fiber loading of 60% by weight or approximately 49% by volume, compared to uncoupled composites and unfilled PP. However, tensile modulus has shown a contrary trend where the uncoupled composites showed some very interesting behavior, with tensile modulus higher than that of a coupled system at identical fiber loadings. They believed that the results were attributed to the possibility of a high-stiffness trans-crystalline zone forming around the fiber in the unmodified systems, where it could indirectly lead to the high tensile modulus observed. Instead of a static mechanical assessment, a few researchers are interested with the dynamic mechanical properties of kenaf fiber reinforced composites. Using special dynamic facilities, namely the split Hopkinson pressure bar apparatus, Omar et al. [49] exposed the kenaf fiber reinforced unsaturated polyester under a wide range of strain rates, up to the dynamic region. Interestingly, they found that the compression modulus, compressive strength, and the 2.5% of flow stress of kenaf fiber reinforced composite, increased greatly with an increasing strain rate. Furthermore, the composite shows a certain level of strain rate sensitivity of flow stress towards the strain rate applied up to a certain extent.

In summary, a comparative study of the mechanical properties of kenaf fiber reinforced composites and other natural fibers, is collected together, and shown in Figs. 9 and 10. Data for the other natural filler types was taken from existing literature, where these composites were fabricated using polypropylene films, with natural fiber layers randomly spread between them [6,12,55,56]. From these figures, the benefit of the kenaf fiber reinforced thermoplastics is apparent. Through repeated testing, both the 30% and the 40% kenaf polypropylene samples demonstrated equivalent tensile

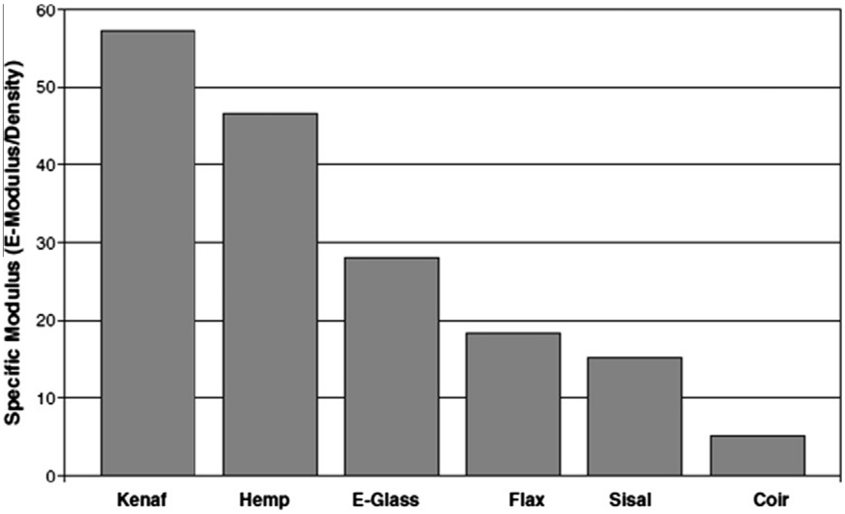


Fig. 11. Comparison of specific modulus of kenaf fiber with several other fibers.

strengths. When compared to the other natural fiber reinforced polypropylene systems, both the 30% and the 40% kenaf polypropylene systems provided a tensile strength that was very similar to the flax and hemp polypropylene systems, while providing tensile strengths that are greater than either coir or sisal polypropylene systems. When comparing flexural strengths of the materials, the 40% kenaf polypropylene samples performed significantly better than the 30% kenaf/PP samples. The 40% kenaf/PP was equivalent to the flax/PP, higher than the hemp/PP, and almost double that of the coir/PP and sisal/PP systems. The 30% kenaf/PP showed results that were equivalent to the 40% hemp/PP system, while also outperforming the coir/PP and sisal/PP systems. Meanwhile, Fig. 11 illustrates that these kenaf/PP composites have a higher modulus/cost modulus than sisal, coir, hemp, flax, and E-glass. Sources of the density and cost data can be found in Table 5. These results demonstrate that the 40% and 30% by weight kenaf polypropylene composites, that were compression molded, were comparatively in favor with the more commonly used hemp and flax fiber polypropylene composites that had 40% fiber by weight. This reinforces the idea that compression molded kenaf polypropylene thermoplastics can provide an alternative that has less fiber, but similar performance at a lower weight and potentially, an even lower cost [57,58].

2.5.2. Thermal properties

Thermal analysis studies are another essential characterization, which needs to be considered to fully distinguish the overall behavior of kenaf fiber reinforced composite. For this reason, three regular characterization methods were employed, namely Different Scanning Calorimetric (DSC), Thermo Gravimetric Analysis (TGA), and Dynamic Mechanical Analysis (DMA). From the DSC scan, several crucial parameters could be estimated, such as the glass transition temperature (T_g), melting temperature, crystalline level, and oxidation [59]. Meanwhile, from the TGA measurement, the mass of the sample as a function of the temperature can be measured. Changes of mass usually occur during sublimation, evaporation, decomposition and chemical reaction, and magnetic or electrical transformation of the material, that is directly related to thermal stability [60]. Particularly, Julkapli and Akil [60] performed both DSC and TGA on kenaf-filled chitosan biocomposites in order to evaluate their thermal characteristics. During the DSC analysis, the heating scan was performed twice and they found that all samples showed a broad endothermic peak during the first heating scan, which was associated with the hydration of water. Meanwhile, for the second heating scan, it showed the decreasing endothermic temperature by the addition of kenaf dust content in the chitosan film. The authors claimed that this trend was attributed to the formation of hydrogen bonding. However, no clear evidence of changes in terms of enthalpy values (ΔH) was observed with the increasing kenaf fiber content. In the meantime, the TGA results shows that the addition of kenaf dust in the chitosan film does not give any significantly change in the thermal stability of chitosan film. On the other hand, DMA is another versatile thermal facility, which can be manipulated to study the correlation between the thermomechanical properties of material as a function of temperature and deformation. The DMA measurement consists of observation of the time-dependent deformation behavior $x(t)$ of a sample under periodic, mostly sinusoidal deformation force with very small amplitudes $F(t)$. Thus, it is possible to calculate, for example, Young's modulus, E' (storage modulus) and E'' (loss modulus), as well as the mechanical loss factor, tan δ (damping), as a function of temperature and deformation [61]. Nishino et al. [7] performed the DMA testing on the kenaf sheet, PLLA film, and its composites. They found that, the kenaf/PLLA composites showed a higher value of dynamic storage modulus (E') than that of kenaf sheet and PLLA film. Furthermore, this high storage modulus was maintained up to the melting point of PLLA (T_m = 161 °C from the DSC measurement). Though the tolerance was limited by the intrinsic property of the matrix resin, the composite showed a relatively high thermal resistance. For the composite, the main tan δ peak, assigned as the glass transition of PLLA, shifted to a

Table 5
Density and cost of glass fibers and natural/bio-fibers.

Fiber	Density (g/cm^3)	Cost (kg^{-1})
Flax	1.4–1.5	~$0.40–$0.55
Hemp	1.48	~$0.40–$0.55
Jute	1.3–1.45	~$0.40–$0.55
Sisal	1.45	~$0.40–$0.55
Ramie	1.50	~$0.44–$0.55
Pineapple leaf	1.53	~$0.40–$0.55
Cotton	1.5–1.6	~$0.44–$0.55
Coir	1.15	~$0.40–$0.55
Kenaf	1.4	~$0.40–$0.55
Softwood	1.4	~$0.44–$0.55
Hardwood	1.4	~$0.44–$0.55
E-glass	2.5	~US $2
S-glass	2.5	~US $2

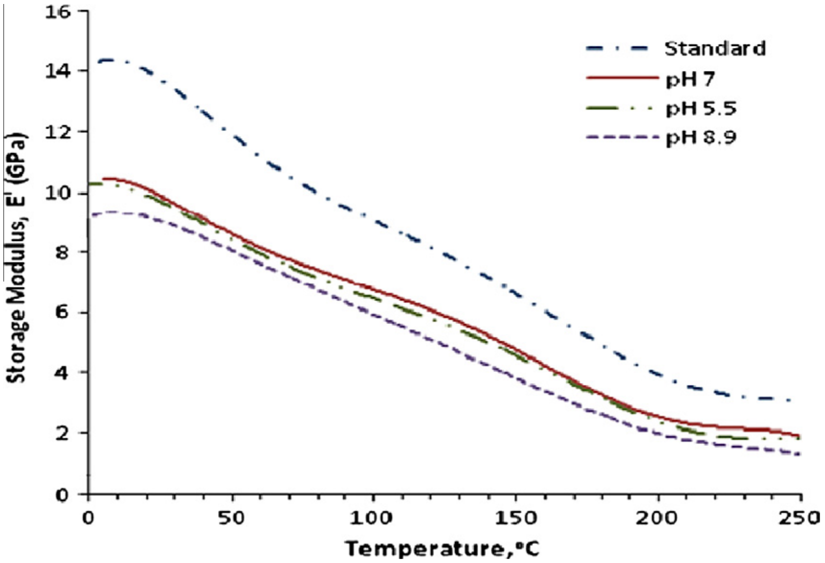


Fig. 12. Variations of storage modulus, E', for kenaf fiber reinforced composite after exposure to various solutions for 24 weeks.

higher temperature and the absolute value decreased. This suggests a strong interaction between the kenaf fiber and the PLLA resin, which reflects on the mechanical reinforcement of the kenaf fiber. Another interesting DMA result was achieved by Mazuki et al. [61] where they specifically studied the degradation of the dynamic mechanical properties of kenaf fiber reinforced composites, after immersion in various solutions. From their overall observations, they conclude that the thermal mechanical properties of kenaf fiber reinforced composite, in terms of a tan δ, storage modulus, and loss modulus, were reduced after immersion in various solutions, as illustrated in Figs. 12 and 13. Statistically, kenaf fiber reinforced composite immersed in sea water (pH 8.9) showed the highest reduction, followed by acidic rain water (pH 5.5), and distilled water (pH 7). Theoretically, the reduction pattern recorded for tan δ is attributed to the increase of ductility caused by the restriction of movement of polymer molecules, after the immersion process for all samples tested. Incorporation of reinforcing fibers restricts the mobility of the polymer molecules under deformation, and thus, raises the storage modulus values and reduces the viscoelastic lag between the stress and the strain. Hence, the tan δ values of composites are reduced [62,63]. Meanwhile, the decreased value of storage modulus for immersed kenaf fiber reinforced composite, was due to the damaged matrix, deteriorated interfacial adhesion, and bond strength, between matrix and fiber. The behaviors of the chemicals combination of chains, the Van der Waals bonding, and the hydrogen bonding in the molecular construction of the polymer, were responsible for the ability of the material to bear foreign stress [63]. When water molecules entered the polymer, the hydrolysis and plasticization of the matrix would damage the chemical combinations and bonding. In the case of experiencing stress, when a greater strain was induced, it would indirectly lead to a decrease of the storage modulus. Moreover, It has been reported that due to the increased polymer chains mobility in composites with poor adhesion, the storage modulus of these materials were lower than that of weak interfacial bonding [64]. Instead of normal practice, the DMA machine can also be manipulated to determine the heat deflection temperature of kenaf fiber reinforced composites, as revealed by Liu et al. [65]. Generally, Heat Deflection Temperature (HDT) is defined as the temperature at which a material deflects by 0.25 mm under the application of a load (0.45 MPa). According to Liu et al. [65] the heat deflection temperature of kenaf/soy based plastic biocomposites, showed a significant increase of approximately 36 °C, due to the processing method, where the modulus at room temperature is independent of the processing method. However, the rate at which the modulus decreases with temperature for compression molded samples is lower than that observed for injection molded samplings, as shown in Fig. 14. This improvement will cause a decrease in the creep rate under a given load, resulting in higher HDT values. In addition, HDT values increased with increases in fiber content (as well as fiber length), reflecting the dependence of the modulus on these variables. Ultimately, they believed that improving a composite's HDT by optimizing fiber size, fiber content and processing method could reveal new uses for kenaf/soy based plastic biocomposites.

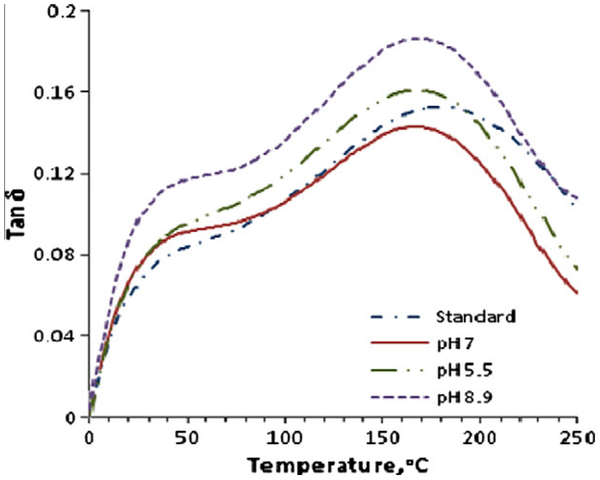


Fig. 13. Variations of tan δ, for kenaf fiber reinforced composite after exposure to various solutions for 24 weeks.

2.5.3. Water absorption properties

As discussed previously, water absorption of natural fiber reinforced composites is a serious concern; especially for their potential outdoor applications. For a given composite system, the water absorption characteristic depends on the content of the fiber, fiber orientation, temperature, area of the exposed surface, permeability of fibers, void content, and the hydrophilicity of the individual components [40,66–68]. According to the work reported by

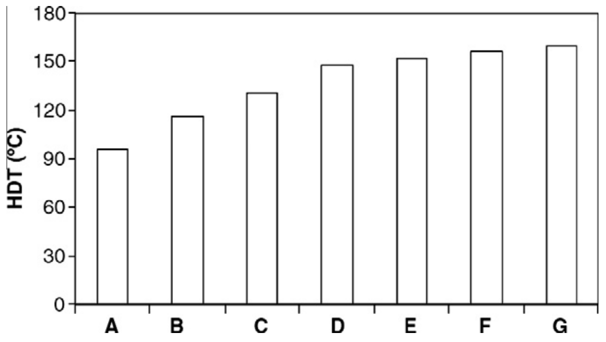


Fig. 14. Heat deflection temperature of kenaf fiber reinforced soy based biocomposites for (A) 30 wt.% kenaf fiber injection molded composite, (B) 33 wt.% 6 mm kenaf fiber compression molded composite, (C) 55 wt.% 2 mm kenaf fiber compression molded composite, (D) 56 wt.% 6 mm kenaf fiber compression molded composite, (E) 57 wt.% 25 mm kenaf fiber compression molded composite, (F) 53 wt.% 50 mm kenaf fiber compression molded composite, and (G) 54 wt.% long kenaf fiber compression molded composite.

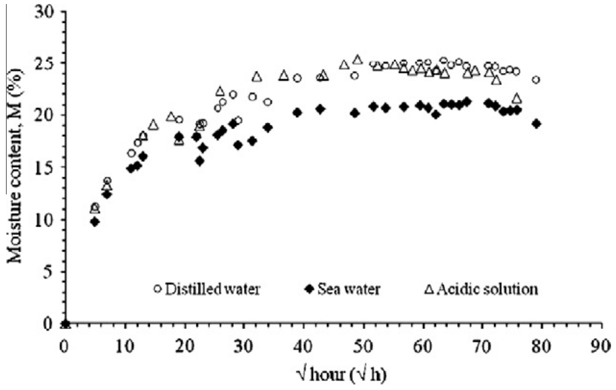


Fig. 15. Water absorption content curves in distilled water, sea water, and acidic solution for compression specimens.

Nosbi et al. [68] the water absorption behavior of kenaf fiber reinforced unsaturated polyester composites was found to follow a Fickian's behavior, where it reached equilibrium at a certain specific immersion time. A more recent study by Mazuki et al. [61] also reported a similar trend. Interestingly, they found that the kenaf fiber reinforced composite shows a different magnitude of absorption characteristics under various solutions, as shown in Fig. 15. From Fig. 15, it is clear that the moisture content increases with immersion time. Similar findings were reported by [66,69,70]. However, as can be seen in Fig. 15, the increase in weight is not consistent with respect to the immersion time. At the beginning of the curve (up to 17 days of immersion), the weight increased sharply, demonstrating the rapid moisture penetration into the composite materials. This trend was true for all solutions considered in their study. They claimed that this phenomenon was attributed to the penetrability of water and capillary action, where it becomes active as the water penetrating into the interface through the voids induced by swelling of the kenaf fibers. The rate of water absorption slows after 20 days of immersion, before reaching a saturation state after 260 days of immersion. Interestingly, after 104 days of immersion (p50 h), the recorded weight gain of the specimen immersed in an acidic solution is almost similar to the one immersed in distilled water. Based on the pH analysis of the solution, it was found that the neutralization process occurred in the acidic solution, where the pH of the acidic solution was almost neutral (approximately pH 7) after 260 days of immersion, in comparison with the initial pH of 3 at the beginning of the test. Meanwhile, in the saturated state (after 260 days of immersion), weight gain of the kenaf fiber reinforced composite in seawater, was the lowest. They believed that this incident was due to the presence of ionic salt in the seawater, blocking the diffusion path after a long-term exposure, thus slowing down the absorption process.

2.6. Processing of kenaf fiber reinforced composites

2.6.1. Compression molding

Compression molding is one of the conventional techniques for producing polymer matrix composites and is widely accepted as the manufacturing process, due to its simplicity [65,71–73]. However, one of the main obstacles that need to be addressed in the fabrication of kenaf fiber reinforced composites is the uneven fiber distribution in the composite system. As Zampaloni et al. [71] pointed out, kenaf fibers are difficult to manually separate and visually disperse evenly during manufacturing. Therefore, authors have defined the optimal fabrication method for the molding process, which is the layered sifting of a fine polypropylene powder and chopped kenaf fibers. The end product, fabricated by this molding technique, is far better (in terms of filler distribution) than that of other processes, such as (a) sandwiching layers with long fibers, (b) sandwiching layers with chopped fibers, (c) kenaf–polypropylene composites fabricated by dry mixing, and (d) kenaf–polypropylene composite fabricated by multiple layering of powder and fibers, as can be observed in Fig. 16. The new sifting process involves sprinkling the polypropylene powder as a base-layer, adding individually sifted fibers, sprinkling more polypropylene, until all of the desired materials are used. Unfortunately, problems occur during the PP sifting stage, due to the larger size of PP used. However, this difficulty has been overcome by using a finer PP to make spreading and sifting easier. Finally, the authors proved that this process is efficient enough to enable better fiber distribution (see Fig. 16). On the other hand, with a small amount of modification, the orientation of the fiber within the composite system can also be manipulated and altered via this technique. According to Shibata et al. [74] fiber oriented kenaf reinforced composites can be produced using additional fabrication steps added into compression molding process. The steps are as follows: (1) Half of the fibers were put into the mold through the clearances of the slit jig, as shown in Fig. 17. At this time, the bottom of the cylindrical slit jig was in contact with the mold bottom, in order to maintain fiber orientation. (2) The slit jig was pulled out carefully and all of the resin was put into the mold. (3) The slit jig was put into the resin again, and the rest of the fiber was put onto the resin thorough the clearances of the slit jig. A wider slit jig would be expected to produce composites with a wider fiber orientation distribution. Meanwhile, for random distribution of kenaf reinforced composites, fiber was put into the mold without any previous mixing. All composite specimens (random and oriented distribution) were fabricated using a cylindrical steel mold and the press forming was performed at 160 °C, 10 MPa for 10 min. The final products can be seen in Fig. 18. Not-withstanding previous beliefs, compression molding still remains both relevant and efficient in producing high quality end products, especially in the fabrication of kenaf fiber reinforced composites.

2.6.2. Pultrusion

Evolution of manufacturing processes of polymer composites has introduced the unique technique of the pultrusion process. Recently, this technology has been and, given all of the available evidence, is likely to remain a very attractive application and growth sector of the whole polymer composites industry. Moreover, pultruded profiles are already recognized as a high-quality industrial product, capable of satisfying a wide range of high performance and structural element requirements [75].

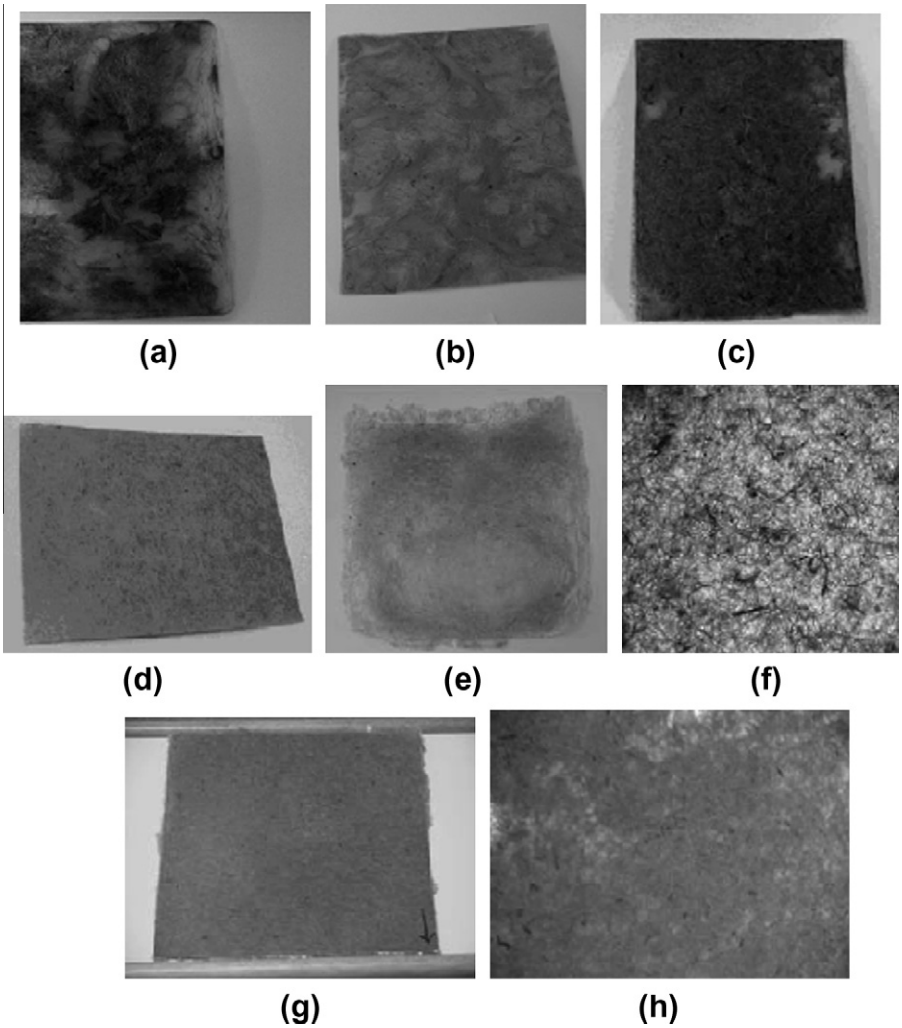
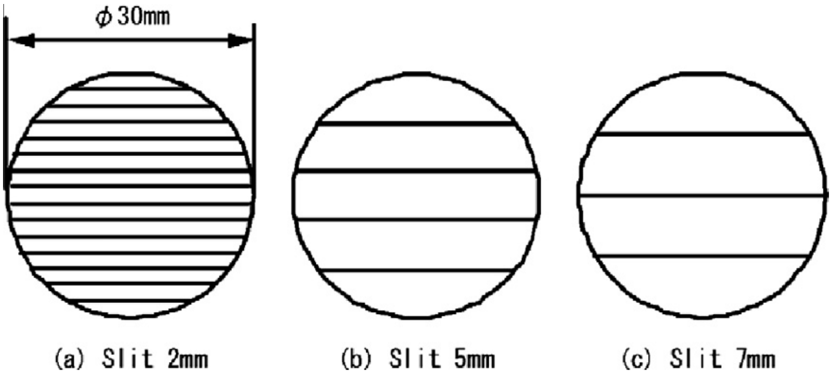


Fig. 16. (a) composite fabricated by sandwiching layers with long fibers, (b) composite fabricated by sandwiching layers with chopped fibers, (c) kenaf–polypropylene composites fabricated by dry mixing, (d) kenaf–polypropylene composite fabricated by multiple layering of powder and fibers, (e) and (f) kenaf–polypropylene composite fabricated by multiple layering of powder and fibers, and (g) and (h) final kenaf–polypropylene biocomposite with 30% fiber by weight.



(a) Slit 2mm (b) Slit 5mm (c) Slit 7mm

Fig. 17. Slit jigs for aligned fiber composites.

Previously, implementation of the pultrusion technique in fabricating natural fiber reinforced composites, was only down to two primary cost driving factors, which are raw materials and labor [76]. However, from a series of mechanical tests, which showed pultruded samples, they also displayed a significant improvement in terms of structural performance characteristics, such as flexural strength, modulus, and impact resistance [76]; which is appropriate for various engineering products. Specifically, a study on the performance of pultruded natural fiber reinforced composites, as a building material for door frames, has been successfully obtained by Van de Velde and Kiekens [75]. They found that pultruded profiles are dimensionally stable and retained adequate mechanical strength under all aging conditions. Moreover, an optimum utilization of coating material (polyurethane), has also improved weathering

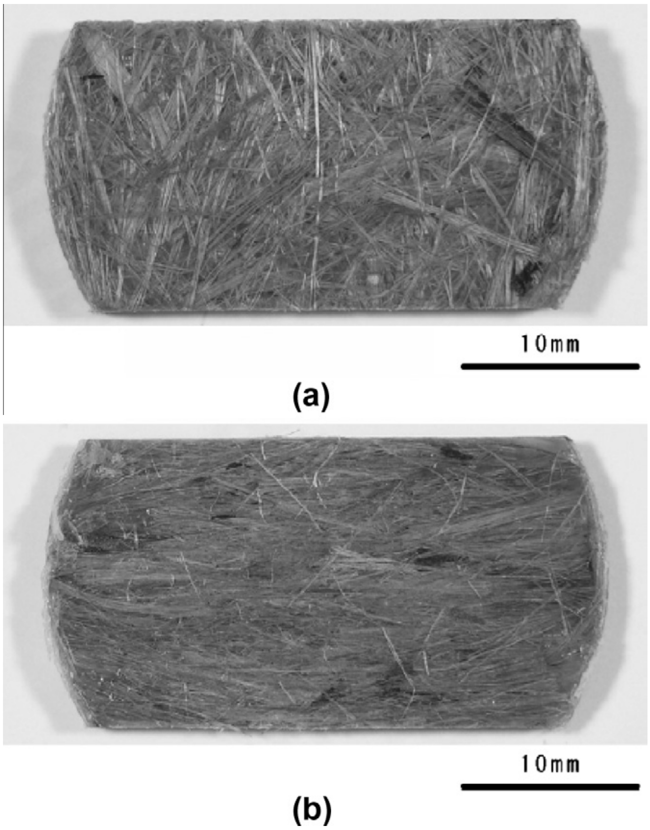


Fig. 18. Appearance of flexural specimens: (a) kenaf, random (b) kenaf, fiber oriented with slit size 2 mm.

performance of the pultruded samples, as experienced on installed door frames, outdoors. With regards to the advantages offered by the pultrusion technique, the fabrication of natural fiber reinforced composites was first introduced and reported by [75]. Recently, a group of scientists were extensively involved with the pultrusion technique for a large scale production of kenaf fiber reinforced composite samples, as reported by [49,61,68]. During a series of tests, they found that pultruded samples performed better in terms of mechanical and thermal properties, compared to samples that were fabricated through ordinary manufacturing processes.

2.6.3. Solution blending

Unlike normal sample preparation, the solution blending process is more suitable for the fabrication of thin film samples. Therefore, it has become an alternative process that is frequently used to produce kenaf fiber reinforced composites, especially in the form of thin film [77–79]. Julkapli et al. [78] particularly implemented the technique in order to produce thin films of kenaf-filled chitosan nanocomposites. Their process began with the preparation of a chitosan solution. In this case, the chitosan solution was prepared by dissolving chitosan powder in 0.1 M acetic acid, at a ratio of 1:50. Next, kenaf dust was added to the solution based on the weight percentage of chitosan. An agglomeration problem appears in the mixture, and thus, a homogenizer is added with high-speed stirring. In spite of providing fast and efficient mixing of kenaf and chitosan, the homogenizer also generates a considerable amount of air bubbles. During the solution casting process, the well mixed chitosan/kenaf dust solution was cast evenly onto a glass plate. After that, the chitosan/kenaf film was oven dried overnight at 60 °C, then neutralized using 0.1 M NaOH solution, and dried further at room temperature for 5 h. Finally, the films are stored in a proper place (i.e., desiccators) until required for further use. Although the technique gives the impression of being difficult and fussy, it somehow offers many advantages compared to other thin film manufacturing processes. The advantages are: a higher quality (uniformity) thinner film, free from pinholes and get marks, purity and clarity, possibility to produce patterns or dull finishes, etc. However, extra precautions need to be considered for this manufacturing process. In open air conditions, this technique is highly embroiled with contaminants: emulsifiers, residuals of the initiators, chain transfer, stabilizers, etc. which can alter the properties of the end products.

3. Conclusions

Research on kenaf fiber reinforced composite is generating increased attention due to its excellent properties and ecological considerations. A brief discussion of kenaf fiber reinforced composites is given along with a review, in the previous study. The aforementioned topics are aimed at bringing scientists to look at the potential of kenaf fiber as an alternative medium to replace conventional materials or synthetic fibers as reinforcement in composites. Processing techniques for kenaf fiber reinforced composite are well documented and many of their main properties have been studied. In general, the use of kenaf fiber reinforced composite can help to generate jobs in both rural and urban areas; in addition to helping to reduce waste, and thus, contributing to a healthier environment. However, looking at future demands, more crucial studies are required on product commercialization and manufacturing processes, especially for large scale end products.

4. Developments for the future

Kenaf fiber reinforced composite shows a bright future among other natural fiber reinforced composites for the several specific reasons that were highlighted in the previous discussion. The most interesting development of kenaf fiber reinforced composite is utilizing its availability and readiness to be used with various manufacturing processes that have never been associated with other natural fibers before, such as pultrusion and potentially, filament winding. Based on this brief review, the application of kenaf fiber reinforced composite as an alternative composite material, especially in building and construction, is highly plausible with both lightweight and low cost as its main driving forces.

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