A review on the extraction of pineapple, sisal and abaca fibers and their use as reinforcement in polymer matrix

S. Radoor¹, J. Karayil², S. M. Rangappa¹, S. Siengchin^{1*}, J. Parameswaranpillai³

¹Department of Mechanical and Process Engineering, The Sirindhorn International Thai-German Graduate School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok, 1518 Wongsawang Road, Bangsue, 10800 Bangkok, Thailand

²Government Polytechnic Women's College, Calicut, Kerala, India

³Center of Innovation in Design and Engineering for Manufacturing, King Mongkut's University of Technology North Bangkok, 1518 Wongsawang Road, Bangsue, 10800 Bangkok, Thailand

Received 15 July 2019; accepted in revised form 9 October 2019

Abstract. In recent years, researchers across the globe have switched from synthetic fibers to natural fibers for the fabrication of composites. The desirable properties of natural fibers which attracted researchers, as well as academicians, are its low density, easy availability, environmentally friendly nature, biodegradability, and high specific strength. Hence in the last decade, there is tremendous progress in the development of natural fiber-reinforced composites for various industrial applications. The current review focused on the recent progress in natural fiber-reinforced polymer composite. The natural fibers discussed in this review are derived from leaves, namely pineapple, sisal, and abaca. The extraction and processing of these fibers are briefly outlined. The properties and application of natural fiber-reinforced composites are also addressed in this review. One of the drawbacks of natural fiber is its poor compatibility with the polymer matrix. The different treatment methods to improve the fiber-matrix interaction are also summarized in the present review.

Keywords: biopolymers, biocomposites, natural fibers, polymer-matrix composites, chemical treatments

1. Introduction

Polymer matrix composite (PMC) is one of the well-recognized composite materials with attractive properties such as low density, high stiffness, high tensile strength, and high resistance to corrosion and chemicals [1]. Such composites have been employed in various industries ranging from automobiles to more advanced fields such as aeronautics and robotics [2–4]. Matrices used to fabricate polymer composites can be either thermoset (epoxies, polyesters resin, vinyl esters, bismaleimide, and polyamides) or thermoplastic (polyesters, polypropylene, polyphenylene sulfide (PPS), polyether ether ketone (PEEK), and liquid crystal polymers) [5, 6]. To improve the performance of PMC, fiber reinforcements are frequently

employed as they offer some excellent properties such as high strength, high modulus, low coefficient of thermal expansion and chemically inertness [7–9]. Fibers are materials (diameter: 0.00025–0.0125 cm) with a high aspect ratio, *i.e.*, their lengths being several times greater than their effective diameters. Both synthetic and natural fibers are used to reinforce composites [10, 11]. However, the expensive and non-biodegradable nature of synthetic fiber urges researchers to find an alternative material. Therefore, in recent years, there is an increasing trend of replacing conventional synthetic fiber with natural fiber to reinforce polymer matrix as it reduces the environmental issues and depletion of fossil resources [12–15].

*Corresponding author, e-mail: suchart.s.pe@tggs-bangkok.org
© BME-PT

Being derived from natural agro-sources, plant fibers have been employed to fabricate novel composites materials that find applications in automotive industry, aerospace industry and biomedical fields [16–19]. The plant fibers are composed of cellulose, hemicellulose, pectin, lignin, waxes, and water-soluble substances. The main component of plant fibers is cellulose. It is a linear polysaccharide with β (1→4) glycosidic linkage, which provides strength and stiffness to the fiber [20]. Hemicellulose is a hydrophilic branched heteropolysaccharide with shorter number of glucose units than cellulose. The moisture uptake capacity of fiber is associated with hemicellulose [21–23]. Lignin is high molecular weight polymer of monolignols (aromatic alcohols) that is present in the secondary cell wall of the plant. The main role of lignin is to bind the cellulose fibrils thus imparting rigidity to the fiber [24]. Pectin is a complex mixture of polysaccharides with an average molecular weight of about 50 000–180 000 Da and contains galacturonic

acid in high percentage [25]. The distribution of chemical components in plant fibers is known to vary by plant species, growth condition and fiber extraction [26]. The chemical composition of different plant fibers is displayed in Table 1.

Based on the locations of extraction, plant fibers have been categorized into seed fibers (cotton, coir, and kapok), leaf fibers (sisal, pineapple, abaca, henequen, curaua, plassava and fique), bast fiber/stem fibers (jute, flax, ramie, hemp, kenaf, isora and banana), fruit fibers (coir, oil palm and assai) and stalk fibers (wood, bamboo, grass, barley, rice straw, wheat straw and bagasse). The images of different plants, their fibers, and fabrics are displayed in Figure 1. The attractive features of plant fibers are low density, high specific strength, biodegradability, and low cost. The mechanical properties of the fibers depend on their aspect ratio, microfibrillar angle, cellulose content and crystallinity [27]. The mechanical properties of plant fibers are listed in Table 2.

Table 1. Chemical composition of different plant fibers [Reproduced with permission from Elsevier, License Number-4626830253379] [27].

Type of fiber	Cellulose	Lignin	Hemi-cellulose	Pectin	Wax
Jute	61–71.5	12–13	13.6–20.4	0.2	0.5
Flax	71	2.2	18.6–20.6	2.3	1.7
Hemp	70.2–74.4	3.7–5.7	17.9–22.4	0.9	0.8
Ramie	68.6–76.2	0.6–0.7	13.1–16.7	1.9	0.3
Kenaf	31–39	15–19	21.5	–	–
Sisal	67–78	8–11	10–14.2	10.0	2.0
Pineapple	70–82	5–12	–	–	–
Henequen	77.6	13.1	4–8	–	–
Cotton	82.7	–	5.7	–	0.6
Coir	36–43	41–45	0.15–0.25	3–4	–

Table 2. Mechanical properties of plant fibers.

Fiber type	Density [g·cm ⁻³]	Young's modulus [GPa]	Tensile strength [MPa]	Elongation at break [%]	Moisture constant [%]	Failure strain [%]	Microfibrillar spiral angle	References
Flax	1.54	27.5–85	345–2000	1–4	10	1.3–3.3	10	[30, 32]
Ramie	1.5–1.56	27–128	400–1000	1.2–3.8	8.5	3.7	7.5	[32, 33]
Hemp	1.48	70	550–900	1.6	10.8	2–4	6.2	[29, 32]
Jute	1.3–1.46	10–30	393–800	1.5–1.8	12.6	2–3	8	[29, 31, 32]
Sisal	1.45–1.5	9–22	350–700	2–7	11	2–14	20	[30, 32]
Coir	1.2	4–6	175–220	15–30	8.0	15–40	41–45	[29, 32]
Cotton	1.5–1.6	5.5–12.6	287–597	7–8	8.5	6–8	–	[30, 32]
Curaca	1.4	11.8	500–1150	3.7–4.3	–	–	–	[28, 32]
Kenaf	1.5	53	930	1.6	17	–	–	[28, 32]
Pineapple	1.32	60–82	413–1627	2.4	11.8	0–1.6	14	[31, 32]
Bamboo	0.6–1.1	11–17	140–230	–	–	–	–	[32, 33]
Banana	1.35	27–32	529–914	5.3	–	1–3	–	[32]

Figure 1. a) Sisal plant, and its fiber; b) hemp plant, and its fiber; c) kenaf plant, and its fiber; d) pineapple plant and its fiber. (Internet sources).

2. Chemical treatment methods

The main limitation of natural fiber is its poor mechanical strength, poor dimension stability, high moisture absorption, high swelling, incompatibility with the hydrophobic polymer matrix, and low thermal resistance [34–38]. These limitations can be overcome by various chemical and physical treatments [39–42].

Alkaline treatment or mercerization is the simplest and cheapest method to modify natural fibers. It removes the non-cellulose constituent in fibers such as lignin, wax, and oils, induces ionization of the hydroxyl groups of cellulose to alkoxide, and reduces the hydroxyl group content on the surface of fiber [43]. Alkaline treatment thus enhances the surface roughness and hydrophobicity of the fiber, and consequently the adhesion of the fibers with the polymer matrix increases. The alkali treatment of natural fibers is shown in Figure 2. Several authors have utilized alkali treatment for the surface modification of fibers and reported that alkali-treated fibers possess good mechanical property, thermal stability and low water absorption [44–48].

Alkoxy silanes are versatile coupling agents used for the surface treatment of fibers [49]. Interaction of silane with the fibers results in the formation of

Figure 2. Typical structure of a) untreated and b) alkali-treated cellulose fiber [Reproduced with permission from Taylor & Francis, License Number-501499934] [48].

Figure 4. Simple esterification between the acetyl group of acetic anhydride and the hydroxyl group of natural fiber to yield an acetylated product [56]. The reaction of the alkali treatment is followed by the reaction between the fiber and benzoyl chloride. Reproduced with permission from Elsevier, License Number-4626830253379] [27].

Figure 3. Mechanism of the reaction between the silane groups and the functional groups of the natural fibers [Reproduced with permission from Elsevier, License Number-4626830253379] [27].

hydrogen bonds between the hydroxyl end of the silanol and fiber surface. This results in a reduction of the hydroxyl group concentration present on the surface of the fiber and enhances its hydrophobic character (Figure 3) [27, 50]. Several reports are available on silane treated natural fibers for various applications [51, 52].

Acetylation and benzoylation treatment methods are widely exploited by researchers to modify natural fibers. In the acetylation treatment method less polar acetyl group is introduced on the surface of natural fiber whereas, while in benzoylation, a benzoyl group (C_6H_5CO) is introduced (Figure 4). Bledzki *et al.* [53] reported that the acetylated treated flax fiber has high tensile, flexural properties and good thermal stability. Similar results are reported in the literature [54, 55]. Based on FT-IR and SEM analysis Ferreria *et al.* [27] confirm that the benzoylation induces chemical changes on the surface of sisal fiber, which is responsible for its improved adhesion with the polymer matrix.

It is reported that the tensile property of natural fiber/polymer composite increases with peroxide treatment [57, 58]. Here RO free radical generated by the decomposition of peroxide interact with a hydrogen group of the polymer matrix and fiber and

induces grafting of polymer and the fiber (Equations (1)–(4)) [59]:

Sari *et al.* [60] adopted peroxide treatment for simple fiber and showed that the treated fiber/polyethylene possesses better properties than untreated fiber/polyethylene composite. The improvement in tensile properties with peroxide treatment is attributed to the grafting of polyethylene with sisal fiber [57]. Iso-cyanate treatment is another method to improve the surface properties of natural fiber. In this method, the adhesion between the matrix and the fibers is induced by the reaction between N=C=O group of isocyanate with a hydroxyl group of fiber as shown in Equation (5). The moisture present in fiber hydrolyzes isocyanate to urea, which on reacting with the hydroxyl group of fiber improves its moisture resistance ability and mechanical strength [61, 62].

Isocyanate treated fiber-based composites possess good mechanical [63, 64], thermal conductivity [65] and melt flow [66]. Permanganate treatment, sodium chlorite treatment, and stearic acid treatment are the other methods that are commonly used to modify the surface properties of natural fibers [67]. These chemical treatments are depicted in Table 3.

A much less popular surface chemical modification is ‘cationization.’ The cationized fibers have greater affinity for anionic dye as this treatment method allows the introduction of cationic moiety onto the fiber. For example, Kono [68] reported an improvement in

the adsorption of anionic dye from aqueous solution using cationized cellulose hydrogels. Acharya *et al.* [69] reported that the cotton fibers cationized using (3-chloro-2-hydroxypropyl) trimethyl-ammonium chloride (CHPTAC) is a potential candidate for anionic dye removal studies. In addition to this, cationization also improves the nanoparticle adsorption capacity of cotton fiber [70].

Even some researchers have done the treatment of natural fibers by using a crosslinking agent and a catalyst [71–73]. Alimohammadi *et al.* [74] successfully coated carbon nanotube (CNT) on cellulose fiber using 1,2,3,4-butanetetracarboxylic acid (BTCA) as a crosslinking agent and sodium hypophosphite (SHP) as catalyst. The chemical interaction between the cross-linker and cellulose functional group was confirmed by FT-IR spectroscopy. The experimental result shows that CNT coated cellulose fiber show better functionality and thermal stability. The same group [75] induce hydrophobicity in cellulose fiber by introducing silica nano-particles using BTCA and SHP. Sehaqui *et al.* [76] developed carboxylated cellulose nanofibers (CNF) by esterification of wheat fibers with different cyclic anhydrides namely maleic, phthalic and succinic anhydrides. The results revealed that fiber treated with succinic anhydride possess high carboxylation and it could be used in biomedical or electronic applications.

The phosphorylation technique is widely used in medicines to improve the adhesion of cellulose [77]. In the composite material field, this technique is used to enhance the flame retardance and water repellent properties of fibers [78, 79]. Recently El-Shafei *et al.* [80] fabricated a jute composite from phosphorylated nanocellulose (P-NC) and chitosan. The prepared composites are found to possess good thermal stability as well as antibacterial property. The thermal stability of composite is found to be directly proportional to phosphorus content, while the chitosan is responsible for its antibacterial property. Tzanov *et al.*

Table 3. Chemical interaction with fibers [67].

Chemical	Reaction	Effect
Permanganate treatment	$\text{Fiber-OH} + \text{KMnO}_4 \rightarrow \text{Fiber-O-H-O-Mn(OO)OK}^+$	The Mn^{3+} ion-initiated graft polymerization increasing the surface roughness of the fiber
Sodium chlorite treatment	Sodium chlorite has bleaching action on the natural fiber	It makes the fiber clean and rough thereby enhancing the interlocking with the matrix
Stearic acid treatment	$\text{Fiber-OH} + \text{CH}_3(\text{CH}_2)_{16}\text{COOH} \rightarrow \text{CH}_3(\text{CH}_2)_{16}\text{COO-O-Fiber} + \text{H}_2\text{O}$	This treatment makes the surface of fiber more hydrophobic, thereby improving the interaction with the matrix
Acrylonitrile treatment	$\text{Fiber-OH} + \text{CH}_2=\text{CHCN} \rightarrow \text{Fiber-OCH}_2\text{CH}_2\text{CN}$	This chemical modification improves the surface properties of the fiber

[81] adopted enzymatic phosphorylation rather than chemical phosphorylation to improve the colorability and flame resistance of cotton cellulose. Pan *et al.* [82] employed layer by layer (LbL) method to deposit polysaccharides, chitosan and phosphorylated cellulose (PCL) on the surface of cotton fabric. The prepared polyelectrolytes multilayer (PEM) films have better thermal stability and flame retardancy compared with pure cotton fabric.

Layer by layer treatment (LbL)

In today's world, there is a growing concern for the use of toxic materials in various areas of science and technology. This urges researchers to adopt greener techniques for surface treatment. Layer by layer treatment (LbL) is a novel and promising technique and involves the deposition of oppositely charged polymers or nanomaterials onto the surface of fiber [83]. The coated LbL thus acts as interphase and improves the fiber/matrix interaction. LbL technique was found to improve the properties of natural fibers such as its strength [84, 85], wettability [86], flame retardant efficiency [87], antibacterial property etc. Battagazzore *et al.* [85] modify the surface of hemp fibers using chitosan and sepiolite (CH/SEP) and found significant improvement in the mechanical properties of poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)/hemp fibers biocomposites. Cellulose fiber with better hydrophobic character was generated by the adopting LbL self-assembly of cationic polyacrylamide (CPAM) and lignosulfonate (LS). LS nanomaterial was found to be responsible for inducing the hydrophobicity in the fiber, whereas CPAM strengthens the cellulose fiber [86]. Another cheap and eco-friendly treatment for modifying natural fibers is enzyme treatment. González *et al.* [88] report that the *Penicillium echinulatum* cellulose treated sisal fibers exhibit better thermal and crystallinity than untreated fiber. The improvement in the surface roughness of enzyme-treated fiber is due to the removal of impurities such as hemicellulose, pectin, and lignin. A similar result was observed for the enzyme (pectinase, laccase, cellulase, and xylanase) treated jute fiber. The composite reinforced with this treated fiber has higher toughness and mechanical property.

3. Physical treatment methods

Apart from the chemical treatments, physical treatments such as stretching, calendaring, thermal treatment and plasma techniques are available which

improve the mechanical bonding between the natural fiber and the polymer matrix. These treatments alter only surface properties of fiber, not its chemical composition.

3.1. Plasma treatment

Plasma treatment is one of the commonly used physical treatments employed for the surface modification of natural fibers. Plasma is generated by applying electric field into a gas at atmospheric or reduced pressure. Electric field ionizes the gas which leads to the formation of ions, electrons, photons, free radicals, excited atomic and molecular ions [89, 90]. These particles later interact with the fiber and generate new reactive sites and functional groups on the surface, thus induce a change in surface properties of fibers such as wettability and flammability. They also remove contaminants from the surface of fibers making it rougher and thus improving the interlocking between fiber and matrix.

3.2. Corona treatment

This treatment uses a high-frequency discharge to generate plasma (ionized air) and emits light with a blue hue. During the corona discharge, several oxidants such as ozone, atomic oxygen, and oxygen free radicals are generated, which leads to surface oxidation. As a result, there are some modifications of surface structures leading to an improvement in the impact strength and tensile strength of the composites [91, 92].

3.3. Ozone treatment

Ozone treatment employs ozone or fluorine gas to modify the surface of natural fibers. Recently, many researchers are adopting this treatment to enhance the physical properties of natural fibers [93–95]. This method is found to alter the surface morphology and roughness of fibers [96]. Ozone treatment is also found to improve the hydrophilicity of fiber as the ozonized product has greater accessibility to water molecules [97]. Maqsood *et al.* [98] employed ozone treatment for jute fiber and observed good moisture absorption and tenacity than untreated fiber. This is attributed to delignification of cellulosic chain by ozone treatment.

4. Pineapple leaf fiber (PALF)

The pineapple (*Ananas comosus*) is a tropical plant belonging to the Bromeliaceae family and is widely cultivated for its edible fruit [99]. A mature pineapple

plant has about 60–80 sword-like leaves with an average length and width of 55–75 and 3.1–5.3 cm, respectively [100]. It is one of the cheapest and abundantly available sources of natural fibers that finds application in textile industries, paper industry, upholstery, reinforced roofing, manufacture of yarns and reinforcing polymer composites [101–104]. The fibers extracted from leaves of pineapple are white, smooth and glossy with average length and diameter of 50–120 cm and 105 μm respectively. It possesses low density ($1.44 \text{ g}\cdot\text{cm}^{-3}$) and has good hygroscopic nature (1.1%) [105]. The chemical composition of pineapple leaf fiber (PALF) is as follows: cellulose (70–8%), hemicelluloses (18.8%), lignin (5–12.7%), and ash (1.1%) [106]. Other constituents like fat, wax, pectin, uronic acid, anhydride, pentosan, color pigment, inorganic substance, etc. are also present in minor quantities in PALF [107]. The high cellulose content and low microfibrillar angle are responsible for its excellent tensile strength and mechanical properties of the fibers.

4.1. Extraction of PALF

Pineapple fibers are extracted from the leaves of the pineapple plant. The commonly used methods to extract PALF are hand extraction, retting method, raspador, and decorticator method.

4.1.1. Manual extraction

Hand extraction

This is the simplest and primitive method for the extraction of pineapple fiber. Generally, the leaves with-

in the first three days after harvesting are selected for hand-scraping method. The selected pineapples leaves are sorted to remove damaged or diseased leaves and then scraped using materials such as stone, ceramic plate, knife or coconut shells (Figure 5). The scraping process removes the outer waxy layer of leaves thereby leaving behind only fibers. The collected fibers are washed, dried and later waxed to remove the entanglements. The major drawback of this method is that it is tedious, time-consuming, laborious process and has low efficiency [104, 108].

Retting method

Retting is a biological process that employs microbes for extraction of plant fibers. In water retting process, the scratched pineapple leaves are immersed in water or water bodies for 15–20 days. The microorganism present in water softens the leaves by decomposing the non-fibrous matter of leaves such as hemicellulose, pectin, lignin, fat, wax, ash content, and nitrogenous matter [109]. After a few days, the fibers can be easily separated from leaves, which is later washed many times with water and dried in air to get clean pineapple fiber. It is a common practice to employ urea or diammonium phosphate (DAP) for retting process, as it provides an excellent medium for the growth of bacteria. Bacterial retting uses bacteria culture (*Bacillus* and *Clostridium*) for retting method. It is reported by Cueto *et al.* [110] that bacterial retting process produces cleaner fibers with good tensile strength as it converts nonfibrous matter like hemicellulose to α -cellulose.

Figure 5. a) Scraping the upper layer b) extracted pineapple fiber (Internet source).

4.1.2. Mechanical method

Raspador method

This is a versatile and cost-effective method that involves the use of raspador machine. Here the pineapple leaves were fed into the raspador machine (Figure 6), which consists of several blades mounted on a rotating beater. As leaves were introduced into the machine, the blades progressively crush and scarp the leaves thus removing the leaf pulp and leaving behind only fiber. The extracted fiber strands are later dried in the sunlight [106, 111].

Decorticator machine

The basic principle of a decorticator is beating and scratching. A typical decorticator (Figure 7) consists of sets of rollers, namely: squeezing roller, scrapper roller, and plane roller. The rollers crush the leaves, and blades of the roller remove the

Figure 6. Photograph of raspador machine.

Figure 8. Extraction of fibers from PALF M1 machine [114].

Figure 7. Decorticator machine [113].

upper waxy coating of the leaves. The fibers obtained were later washed and dried in air [112]. Recently Yusof *et al.* [114] have developed a novel decorticator machine for the extraction of pineapple fiber. Figure 8 depicts the mechanism of pineapple extraction. Here the extraction is based on scratching mechanism, and blades of decorticator remove some of the waxy layers on the surface of the leaves. Later, the leaves were pulled off from the machines using the hand, and almost all of the waxy coating was removed. The extracted fibers were cleaned and dried.

5. PALF reinforced polymer composites

5.1. PALF-polyester (PS) composites

The desirable properties of polyesters such as high thermal stability, low creep, good chemical resistance, and high T_g make them a potential candidate in the composite industry [115, 116]. To enhance its physical-mechanical properties of polyester composites it is often blended with reinforcing agents, especially natural fibers [117]. Being mechanically strong and cheap, PALF is one of the frequently used reinforcing natural fiber for polyester matrixes [106]. The mechanical properties of PALF-polyester composites at different PALF loading were studied by different researchers [118]. They report that the mechanical properties (tensile strength, tensile modulus, elongation at break, Young's modulus, impact strength, and shear strength) of neat polyester increases with PALF [wt%] and this improvement is attributed to the enhancement of fiber-matrix interaction with fiber loading [119, 120]. However, the mechanical properties are found to diminish at high fiber loading, due to poor dispersion of fiber in the matrix. The variation

of tensile strength of PALF-polyester composites with fiber loading is displayed in Figure 9.

Figure 9. Tensile strength vs optimum fiber loading of PALF/polyester [119, 121–124].

The enhancement of mechanical properties with fiber loading was supported by SEM analysis. The proper dispersion of PALF at low fiber content is visible in SEM images (Figure 10a and 10b). The morphology of high fiber-loaded polyester indicates that there is weak fiber-matrix interaction due to poor dispersion (Figure 10c).

The impact strength of composites plays an important role in the performance of composite materials. Generally, the impact strength of composites increases with fiber [wt%] [126, 127]. Devi *et al.* [119] report that on increasing the PALF [wt%] from 10 to 50 wt%, the impact strength of PALF-polyester composites also increases and reaches a maximum value of $365 \text{ J}\cdot\text{m}^{-1}$. They propose it is due to the porous nature of PALF. A similar trend was noted by Mishra *et al.* [106] for PALF-polyester composite. Daramola *et al.* [122] designed PALF polyester composites by hand lay-up technique using ethyl ketone peroxide and cobalt naphthenate as catalyst and accelerator

Figure 10. SEM images of the fracture surface of PALF polyester composites with different wt% a) 35 b) 40 c) 50 [Reproduced with permission from John Wiley and Sons, License Number-4662911394941] [121, 125].

respectively. The prepared samples were evaluated for their mechanical and water absorption behavior. Their studies suggest that PALF reinforced composite exhibits better mechanical strength than a neat polyester sample. The tensile strength and Young's modulus of the composites increase with the increase in PALF [wt%], which is attributed to the enhancement of fiber-matrix interaction. The optimum value of tensile strength and Young's modulus obtained at 40 wt% loaded PALF are 29.19 and 762.92 MPa, which is 47 and 65% greater than neat polyester. The optimum flexural strength and flexural modulus were obtained at 20 wt% PALF, while the optimum hardness value was obtained at 30 wt% PALF. Meanwhile, the PALF-polyester composite is found to be quite brittle, probably due to the interruption of polymer mobility by the stiff PALF fiber. Owing to its high impact strength these type of composite finds application in areas such as construction materials [128].

Being a hydrophilic fiber, PALF has only weak adhesion with the polymer matrix. Therefore, to improve its interactions with matrix, various surface treatments were employed. Mishra *et al.* [106] utilized surface-treated PALF fiber to fabricate PALF-polyester composites. The studies show that AN (acrylonitrile) grafted PALF-polyester composite exhibits the highest tensile strength (48.36 MPa). The percentage of AN plays a crucial role in the tensile strength of PALF-polyester composites which is reflected in SEM analysis. A low fiber pull-out from the polymer matrix was observed at low percentage of AN (10%), while high percentage of AN was found to diminish the strength of composites, as it makes the fiber more porous. Meanwhile, Motaleb *et al.* [129] report that alkali-treated PALF-polyester composite displayed superior mechanical properties than untreated PALF composite.

Commercially available prosthetic sockets are usually made of fiberglass polyester material. Odusote and Oyewo [130] attempted to develop two biocomposites namely: PALF/polyester and PALF/epoxy biocomposites as a substitute for fiberglass polyester prosthetic sockets. The mechanical properties of prepared thermoset composites were compared with PALF/glass fiber. PALF used in their study was chemically treated with alkali and acetic acid, and volume fraction of fiber ranged from 0–50%. They report that PALF/epoxy composite is a promising candidate for the development of prosthetic knee socket as it

exhibits better tensile strength (62.09 ± 4.47 MPa), impact strength (45.22 ± 1.10 kJ·m⁻²) and flexural properties (53.02 ± 1.20 MPa) than PALF/polyester and glass fiber polyester resins composites.

Due to the high cellulose content of PALF fiber, water absorption behavior of PALF reinforced composites is higher than neat polyester. The water absorption generally increases with the increase in PALF percentage [122]. Devi *et al.* [131] monitored the effect of environmental factors such as thermal aging and water absorption on the mechanical property of PALF-polyester composites. Experimental results show that thermal aging and water absorption leads to a slight reduction in the mechanical property of the composites.

5.2. PALF-polyethylene (PE) composite

LDPE (low density polyethylene) is a hydrophobic polymer with very low water uptake. The water uptake ability of chemically treated PALF-LDPE composites at different fiber loading was investigated by George *et al.* [132]. The results indicate that the water uptake ability of PALF-LDPE composite increases with fiber loading owing to the hydrophilic nature of PALF. However, water uptake of chemically treated PALF-LDPE composites was found to lower than untreated sample. This is attributed to the reduction in the hydroxyl group of PALF, as it is chemically bonded with the matrix. Besides enhancing the water uptake efficiency of composite, the PALF fiber is also found to improve the viscoelastic property and thermal stability of PALF-PP composites [133, 134]. Bahra *et al.* [135] report higher tensile strength and modulus for pineapple/HDPE composite than pristine HDPE.

5.3. PALF-polypropylene (PP) composite

As PALF-polypropylene composite possesses excellent mechanical property it was suggested as an alternative for synthetic fiber-reinforced PP composites [129]. The mechanical properties of PALF-PP composite vary with fiber loading [136–138] and result from the alpha-cellulose nature and low microfibrillar angle of PALF. Their studies also revealed that the alkali-treated PALF/PP composite exhibits superior mechanical properties than untreated PALF/PP composite. The tensile strength of alkali-treated sample (89 MPa) was found to much higher than other natural fiber-reinforced composites such as jute fiber/PP (55 MPa), banana fiber/epoxy resin (45 MPa)

and jute-banana hybrid fiber/epoxy resin (18.96 MPa) [139–141]. Besides improving the mechanical property, alkali treatment also reduces the water uptake ability of composites.

Chattopadhyay *et al.* [142] reported the utilization of both alkali-treated PALF and maleic anhydride grafted polypropylene (MA-g-PP) as compatibilizer results in a significant improvement in the mechanical property of PP matrix. SEM micrographs support the mechanical analysis and confirm good compatibility between PALF and PP (Figure 11). Their study also sheds light on the effect of fiber length on the mechanical and morphological features of composites. Fiber length plays an important role in tailoring the overall strength of fiber. Short fibers are generally preferred over long fiber as the former offers sufficient strength due to its proper orientation and uniform distribution of load in the fiber. In the case of PALF/PP composites, fiber length of 6 mm is found to possess high mechanical properties such as tensile strength, tensile modulus, flexural properties. On increasing the fiber length beyond 6 mm, the properties tend to diminish due to non-uniform distribution of stress and poor fiber-matrix interaction. The thermal stability of PALF-PP composite is found to increase when MA (maleic anhydride) grafted PP along with treated PALF was used. High thermal stability (122 °C) of treated PALF+PP+MA-g-PP composites is due to enhancement in the trans crystallinity and restricted the mobility of polymer chain in the composite.

5.4. PALF- polylactic acid (PLA) composite

As green composites are environmentally benign materials, researchers are interested in fabricating green composites rather than synthetic polymer

composites for various engineering applications. Munawar *et al.* [143] developed a green composite from biopolymer: polylactic acid and natural fiber: PALF. They evaluated the mechanical properties of these composites with respect to PALF-PP composite and found that the mechanical property of composites decreases with fiber loading. The decrease in tensile strength and flexural property is more pronounced in PALF-PLA composites than with PALF/PP. Kaewpirom and Worrarat [144] adopted chemical treatment methods to improve the performance of PALF-PLA composite. PALF modified with MA coupling agent shows better bonding with PLA matrix thus enhancing the mechanical properties. The prepared composites are also found to exhibit optimum thermal stability at low PALF [%]. Their studies also revealed that the tensile properties of PALF depend on the region of extraction (leaf tip, leaf center, and leaf base). The fiber obtained from the leaf tip is found to be ideal for reinforcing PLA matrix as it offers better tensile strength (244 MPa). In a similar work, Huda *et al.* [145] also showed that chemically treated PALF-polylactic acid exhibits better tensile properties, storage modulus, and thermal stability than untreated composites. Agung *et al.* [146] investigated the effect of compatibilizing agent MAPE (maleated anhydride polyethylene) on the performance of PALF reinforced polylactic acid composite. The bonding of compatibilizing agent with PALF and PLA results in reduced water uptake and good mechanical property (tensile strength: 27.83%, flexural strength: 84.5%), which was confirmed by morphological analysis. SEM micrographs of MAPE treated sample display a smaller number of voids (Figure 12) and thus displayed fairly good mechanical performance.

Figure 11. SEM images of the fractured surface of tensile, impact and flexural of treated fiber composite (6 mm fiber length, 10% fiber volume fraction) [Reproduced with permission from John Wiley and Sons, License Number-4662910894454] [142].

Figure 12. Scanning electron microscopic images of fractured PALF/PLA composite: a) untreated b) treated PALF composites [146].

5.5. PALF-hybrid composites

There is great interest in the development of hybrid composites for various applications [147, 148]. A green biodegradable hybrid composite using polylactic acid (PLA) and poly(butylene succinate) (PBS) as polymer matrix and PALF and recycled disposable chopstick fiber as reinforcing agents were designed by Shih *et al.* [149]. The developed hybrid composite exhibit excellent tensile strength, flexural strength, and thermal stability. Yogesh and Rao [150] studied the mechanical properties of pineapple leaf fiber-reinforced vinyl ester with different particulate fillers. Based on their study they report that incorporation of filler enhances the tensile, flexural, impact and inter-laminar shear strengths of the composites. Asim *et al.* [151] developed a high-performance PALF/KF (kenaf fiber) phenolic hybrid composites and suggested it for automobiles and construction industries. The mechanical performance of these composites was further improved by silane treatment. The enhancement of surface roughness of treated fiber and its adhesion with polymer matrix is reflected in the SEM and FT-IR analysis. A similar observation was made in banana/pineapple leaf fiber/ propylene composite. Rahman *et al.* [152] reported that the polymer reinforced with 5 wt% pineapple leaf and banana fiber at a ratio of 3:1, is found to display good mechanical properties (tensile strength 21.5 MPa., Young's modulus 1155 MPa).

6. Sisal leaf fiber

Sisal fibers are generally extracted from the leaves of the sisal plant which belongs to the family *Agave sisalana*. As sisal plant has a fast-growing rate it is

Figure 13. Production of sisal from 2017 [155].

widely cultivated for its fiber. The worldwide production of sisal fiber is estimated to be 200 000 tons per year. The main cultivator of sisal plant is Brazil (Figure 13). The attractive feature of sisal fiber includes its superior mechanical properties, strong resistance to alkali, and oxidizing agents [153, 154].

6.1. Composition and structure

The length and diameter of a typical sisal fiber are 1–1.5 and 100–300 mm respectively. They are cellulose-based fibers and consists of 55–78% cellulose, 8–19% hemicellulose, 2–11% lignin, 1% pectin and 6–10% moisture content [156]. Based on the place of extraction, sisal leaf fiber is classified into mechanical, ribbon, and xylem fibers. The mechanical fibers are extracted from the periphery of the leaf and possess definite shape. It is the toughest among all three fibers and is the most commercially useful form of sisal fiber. On the other hand, xylem fibers

have the lowest strength due to its irregular shape and thin-walled cell. Ribbon fibers have intermediate mechanical strength and are extracted from the conducting tissue in the median line of the leaf [157].

6.2. Extraction of sisal leaf fiber

Commonly used methods to extract sisal fiber are retting, boiling, and mechanical method. Retting is a traditional method for the extraction of sisal fiber. Here, the bacteria will decompose the sisal leaves, and later, the fibers are separated from the pith. The main drawback of this method is that it is time consuming, intensive and the quality of fiber is poor. The boiling method is preferred for the small-scale production of fiber. In this method, the fibers of the sisal plant are boiled by strong heating. The fibers are later washed and dried in air. The mechanical method is suitable for large scale production of fiber and employed a decorticator machine. During the extraction step, the leaves are crushed and scratched by the blades of the decorticator, consequently the surface coating, wax, and pectin are removed, and eventually, only fibers remain. The collected fiber is washed to remove impurities and dried in sunlight [158].

7. Sisal reinforced polymer composite

7.1. Sisal-polyester (PS) composites

Sreekumar *et al.* [159] compare the effect of two different processing techniques (compression molding and resin transfer molding techniques – RTM) on the mechanical properties of sisal fiber/polyester composites. They found that composites developed using RTM method possess better mechanical properties (tensile strength: 67 MPa, Young's modulus: 2196 MPa and elongation at break: 6%) than the compression molding (tensile strength: 57 MPa, Young's modulus: 1868 MPa and elongation at break: 8%). This is attributed to the low void content and better wettability of composite. SEM analysis shows that compression molding technique has strong extensive fiber pull and high void content which results in its

relatively low mechanical properties. Kumar *et al.* [160] implemented a cheap and eco-friendly method to improve the mechanical and wear properties of sisal/polyester composites. Their reports revealed that incorporation of hybrid mustard and pine needle improve the tensile strength, impact energy and wear properties of composites. The adhesion of hydrophilic sisal fiber with hydrophobic polyesters was improved by adopting various chemical treatments such alkali [161, 162], benzoyl and silane treatment [161], admicellar polymerization using hexadecylpyridinium chloride [163] and *N*-isopropyl-acrylamide solution [164]. The treated fiber-reinforced composites possess better tensile, flexural, impact and hardness than untreated composites.

7.2. Sisal-polypropylene (PP) composites

Dynamic mechanical tests were commonly used to understand the stiffness and damping characteristics of composites. The dynamic mechanical property of sisal-polypropylene composites as a function of fiber loading, fiber length, chemical treatment, and temperature were evaluated by Joseph *et al.* [165]. The composite displays a maximum value for storage modulus at 30% fiber loading with an optimum length of 2 mm. This is attributed to the increase in the bonding between fiber and matrix and even distribution of stress across the composites. Elevated temperature is found to weakens fiber-matrix interaction and thus have negative impact on the storage moduli of the composite. The authors also suggest that MA treated fiber composites are superior when compared to other treated composites as their strong chemical interaction between hydroxyl group of cellosic fiber and anhydride group of MA-treated polypropylene. Sun and Wu [166] modify sisal fiber using tetraethyl orthosilicate and γ -aminopropyl triethoxy silane. The presence of active group on the treated fiber is responsible for its improved bonding with the polymer matrix and this is reflected in the mechanical and thermal performance of this composite.

Table 4. Effect of chemical treatments on sisal/polyester composites.

Sisal/polyester composite	Tensile strength [MPa]	Flexural strength [MPa]	Moisture content [%]	Impact strength	References
Untreated	1	13	11.7	1.5 N·m	[161, 162, 163]
Alkali (NaOH)	1.5	14	11.2	0.9 N·m	[161, 162, 163]
Benzyl	2	27	–	–	[161]
Silane	2	26	–	–	[161]
Hexadecylpyridinium chloride	53	89	–	11.8 J/m	[163]
<i>N</i> -isopropyl-acrylamide	331	–	6.6	–	[164]

The effect of aging on the mechanical property of sisal/polypropylene composite was studied by Joseph *et al.* [167]. Their studies show that composite immersed in water shows a minimal value for tensile strength due to the plasticization effect of water. The exposure to UV radiation is found to have an adverse effect on the mechanical property of both treated and untreated composites. Authors propose that UV radiation could have induced decomposition and chain scission of polymer chain thereby leading to a reduction in properties. A similar observation was made by Chow *et al.* [168]. Mukhopadhyay and Srikanta [169] reported that the aged sisal fiber-PP composites have better mechanical properties than fresh sisal fiber. The poor adhesion of fresh fiber with polymer matrix is ascribed to its high moisture content, whereas aged fibers with low moisture absorption can strongly adhere to the polymer matrix.

7.3. Sisal-polylactic acid (PLA) composites

Samouh *et al.* [170] reported that the introduction of sisal fiber to PLA matrix not only enhances the strength but also the impact property of sisal fiber/PLA composite. Sisal fiber/PLA fiber with 15% sisal fiber content exhibit 30.30% of enhancement in Charpy impact strength, which is comparable to other reported works [171, 172]. In addition to this, sisal fiber increases the crystallinity of composite and could be used as a substitute for synthetic nucleating agents for PLA. Chaitanya and Singh [173] compared D-IM (direct injection molding) and E-IM (extrusion injection molding) technique for the production of sisal fiber/PLA composite process. They report that D-IM is preferred for short fibers while E-IM is suitable for both short and long fibers. Orue *et al.* [174] used a different chemical treatment such as silane treatment and alkali treatment for modifying the properties of sisal fiber/PLA composites. An improvement in performance was noticed for composites prepared using alkali and alkali + silane treated sisal fiber. Meanwhile, Kittikorn *et al.* [175] modify sisal fiber using 3-(trimethoxysilyl)propyl methacrylate. The modified sisal/PLA exhibits excellent microbial degradation than untreated sisal fiber composite.

7.4. Sisal-hybrid composites

Mishra *et al.* [176] observed a positive hybrid effect when glass fiber was incorporated into PALF/polyester and sisal fiber/polyester composite. The mechanical properties of sisal fiber/glass hybrid polyester composites were further improved by chemical treatments. Chemically treated sisal fiber/glass hybrid composites possess desirable mechanical properties and less water uptake; therefore, it can find application in building and automotive industries. Filho *et al.* [177] report for the first time the effect of Portland cement on the physic-mechanical properties of sisal-glass fiber hybrid composites. The experimental results revealed that the Portland cement (10 wt%) imparts high flexural strength and stiffness to the composites and therefore could be used for aircraft and structural applications. Recently, Akash and co-workers [178, 179] fabricated low-cost sisal hybrid composites and thoroughly study its mechanical and water absorption properties in terms of fiber loading. Their results revealed that both sisal/coir fiber epoxy composite and sisal/hemp fiber hybrid possess desirable mechanical properties (Table 5). The water absorption behavior of the hybrid composites increases gradually with fiber loading and reaches maximum at high fiber percentage owing to the hydrophilic nature of sisal fiber. Aslan and Tufan [180] suggest sisal/glass fiber composites as a substitute for synthetic glass fiber composites as it possesses similar mechanical performance and better frictional properties than waste glass composites.

7.5. Sisal based biocomposites

A novel biodegradable composite from sisal fiber and starch was developed and the authors suggest it as an alternative for conventional packaging material, polystyrene [181]. Oliveira *et al.* [182] employed bio-based sodium lignosulfonate (NaLS) to improve the fiber-matrix interaction of sisal fiber-phenolic composite.

8. Abaca leaf fiber

Abaca plants (or Manila hemp) closely resemble the banana plant and belongs to Musacea family

Table 5. Comparison of mechanical properties of sisal/hemp and sisal/coir composites.

Samples	Tensile strength [MPa]	Flexural strength [MPa]	Water absorption [%]	Hardness	References
Sisal/hemp	–	83	9	77	[178]
Sisal/coir	48	77	9	–	[179]

Figure 14. Some morphological features of abaca: a) abaca plant b) petiole c) extracted fibers [Reproduced with permission from Springer Nature-501499934] [185].

(Figure 14). They are generally seen in a shady and humid area and grows abundantly in Philippines, Ecuador, and Costa Rica. A mature abaca plant reaches up to a height of 13–22 feet with a pseudo-stem of about 6–15 inches in diameter. There are around 25 fiber-bearing stalks that produce 12–25 leaves. The inner leaves of abaca contain less fiber than outer leaves [183]. Abaca fiber is obtained from petioles of abaca leaves, and the major component of the fiber is cellulose (56–63%), hemicellulose (20–25%), and lignin (7–9%). It possesses exceptional strength and is found to be tougher than cotton and sisal [184]. In addition to this, abaca fiber possesses good flexibility and water resistance. An important application of abaca fiber is in the production of ropes, woven fabrics, currency notes, cigarette filter papers, vacuum bags, tea bags, paper pulp, materials for car parts, etc. Owing to its superior mechanical strength, it also finds application as a reinforcement material for composites. Table 6 shows the comparison of the chemical composition and physical properties of abaca with other natural fibers.

8.1. Extraction of abaca fiber

The common methods to extract abaca fiber from abaca plants are tuxying and stripping. In tuxying method, abaca fibers are separated by inserting a special knife known as a tuxying knife between the inner and outer layers of the leaf sheath. The collected fibers by either hand stripping or spindle stripping. Both hand stripping or spindle stripping method are used to clean the fibers. Hand stripping is a tedious one, and only 1% of the fiber is recovered by this method. Spindle stripping involves the use of a spindle which is in motion by an electric motor. Here 1.5 to 2% of fiber is recovered [193]. Another method to extract the abaca leaf fiber is called decortication. Here blade of decorticator removes the primary and secondary fibers from the sheaths. Compared to traditional hand stripping and spindle stripping methods, decorticator method produces better fiber yield. The extracted raw fibers are sun-dried and are then graded based on fiber quality. Proper drying is essential for obtaining a good quality of fiber.

Table 6. Comparison of chemical composition of abaca from different studies.

Cellulose [%]	Hemicellulose [%]	Lignin [%]	Moisture content [%]	References
60.8–64	17.5–21	12–15.1	–	[186]
66.43	30.7	13.6	0.7	[187]
63.7	17.5	15.1	7	[188]
56–63	15–17	7–10	–	[189]
56–63	20–25	7–9	–	[190]
68.32	19	12–13	10–11	[191]
63.32	17.32	8.50	0.76	[192]

9. Abaca reinforced polymer composite

9.1. Abaca-polyester (PS) composites

The effect of untreated and acetic anhydride (AA) treated abaca fiber on the biodegradability of polycaprolactone (PCL), poly(3-hydroxybutyrate-co-3-hydroxy valerate) (PHBV), poly(butylene succinate) (PBS) and poly(lactic acid) (PLA) was studied by Teramoto *et al.* [194]. Soil burial test shows that abaca fiber accelerates the biodegradability of this aliphatic ester thus implying that abaca fiber plays an inevitable role in the biodegradation of aliphatic polyester. When compared to treated fiber, untreated fiber causes faster biodegradation of the composite. A similar type of work was reported by Shibata *et al.* [195], and later the same group [196] schematically studied the effect of fiber content, length, and surface treatment on the mechanical properties of PHBV/abaca fiber composite. Optimum tensile strength and flexural modulus were observed when fiber loading was 20 wt%, and fiber length was 5 mm. The flexural property of this composite is comparable with PHBV/glass fiber composite (flexural strength and modulus of PHBV/GF: 38 and 2600 MPa, flexural strength and modulus of PHBV/abaca: 34 and 1450 MPa and flexural strength and modulus of PHBV/untreated abaca: 27 and 1200 MPa).

9.2. Abaca-polypropylene (PP) composites

Bledzki *et al.* [197] made a comparison of properties of abaca/PP with jute/PP and flax/PP composites. They observed that abaca/PP composite (4.3 mJ/mm² and 73 MPa) exhibit better damping and flexural properties than jute/PP (3.1 mJ/mm² and 70 MPa) and flax/PP (3 mJ/mm² and 69 MPa) composite. The properties of PP/chemically treated abaca are summarized in Table 7 [192, 198-200]. The strong compatibility of chemically treated fiber and polypropylene results in improved performance, which is visible from SEM micrographs (Figure 15).

Liu *et al.* [200] studied the effect of surface modification on the transverse thermal conductivity (TTC) of abaca fiber-reinforced epoxy composites. They observed that mercerization and silane treatment improve the TTC of the composites (TTC value for untreated fiber 0.23 W/(m·K) and silane treated fiber 0.34 W/(m·K)). Enzymes have to use to modify the surface of natural fibers [201]. It removes surface impurities such as wax, lignin, fat, etc. which are responsible for weak interaction between fiber-matrix. Bledzki *et al.* [202] in their work employed enzymes as well as chemical methods to improve performance of abaca fiber-polypropylene composites. Experimental results revealed that enzyme-treated fiber

Table 7. Mechanical properties of abaca fiber with different chemical treatment.

Chemical treatment	Tensile property [MPa]	Flexural property [MPa]	Water absorption [%]	References
Untreated	–	–	160	[192]
Alkali	–	–	63	[192]
Untreated	26	47	–	[198]
Benzene diazonium	30	55	–	[198]
Maleated PP	57	–	–	[199]
Untreated	11	–	–	[200]
Silane	29	–	–	[200]

Figure 15. SEM images of a) untreated abaca fiber b) NaOH treated abaca fiber c) maleated polypropylene abaca fiber [192, 197].

Table 8. Mechanical properties of abaca fiber with different chemical and enzyme treatments [202].

Fibers	Tensile strength [MPa]	Flexural strength [MPa]	Moisture absorption [%]	Impact strength [mJ/mm ²]
Abaca	30	52	15	4.2
Maleic anhydride	42	75	9	4.1
Natural digestion	37	58	12	4.4
Fungamix	45	72	8	5

composites possess better mechanical and rheological properties than chemically treated composite.

9.3. Abaca-hybrid composites

Venkatasubramanian *et al.* [203] fabricated a hybrid abaca/banana/glass Bisphenol-A polyester composite with good mechanical properties with applications in the field like automobile, packaging industry, etc. Vijaya Ramnath *et al.* [204] fabricated hybrid natural fibers and compared the properties with single natural fiber composites like abaca and jute. The composite is fabricated with jute and abaca fiber as intermediate layer and glass fiber laminate as top and bottom layer. They are orientated in opposite direction to maintain the strength in all directions. It found that the mechanical properties of abaca-jute-glass hybrid composites are dependent on the fiber orientation. The morphological characterization clearly shows the fiber failure, voids and fiber pull out after mechanical measurements.

9.4. Other composite of abaca fiber

Kim *et al.* [205] investigated the effect of plasma treatment on the water uptake and tensile properties of abaca/epoxy composites. The authors claimed that plasma treatment improves the fiber-matrix compatibility and improves the tensile property of composites. Interestingly, the water uptake tendency decreases with plasma treatment due to the reduction in the hydrophilicity of the fiber. Waste abaca fibers were used to develop an eco-friendly geopolymer

composite. Malenab *et al.* [206] employed sodium hydroxide and aluminum sulfate to modify waste abaca fibers and successful removal of lignin, hemicellulose, and pectin from treated abaca fibers were confirmed by FT-IR and TGA analysis. SEM (Figure 16) was complementary to FT-IR and TGA and supports a rougher surface for treated fiber. Thus, abaca fiber-reinforced geopolymer composite exhibited improved flexural strength.

10. Conclusions

The recent surge of interest in agro waste-based composites has lead to the development of various composites that are environmentally friendly and cost-effective. These composites are able to meet specific demands like heat and chemical resistance, mechanical strength, electrical properties, flexibility, etc. thus causing its application in the more advanced field such as aerospace, military, automobile, household applications etc. Despite several advantage natural fiber-based composites are difficult to commercialize due to poor compatibility with polymer matrix, poor wettability, high moisture uptake, and less durability. The limitation of natural fibers could be overcome by surface treatment. In our review we have shed light on the treatment method to improve the properties of agro-waste such as pineapple, sisal, and abaca. Exploration of cheap and economical treatment method will be an area to be explored by the researchers. Hybrid fiber composite is an emerging sector of material chemistry. The development of

Figure 16. Scanning electron microscopy (SEM) images at low and high magnification of raw (untreated), NaOH-treated and $\text{Al}_2(\text{SO}_4)_3$ -treated abaca fibers: (a) raw (untreated); (b) NaOH treated; (c) without NaOH pre-treatment; 12 h soaking; final pH = 6; $d = 4.5$; and (d) with NaOH pre-treatment [206].

novel hybrid fiber composites to meet the demands of modern world could be another area to be focused.

Acknowledgements

The study was supported by the King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand through the Post-Doctoral Program (Grant No. KMUTNB-62-Post-02 to SR)

References

- [1] Mallick P. K.: Composites engineering handbook. Taylor and Francis, New York (1997).
- [2] Mangalgiri P. D.: Composite materials for aerospace applications. Bulletin of Materials Science, **22**, 657–664 (1999).
<https://doi.org/10.1007/BF02749982>
- [3] McIlhagger A., Archer E., McIlhagger R.: Manufacturing processes for composite materials and components for aerospace applications. in 'Polymer composites in the aerospace industry' (eds.: Irving P. E., Soutis C.) Elsevier, Amsterdam, 53–75 (2015).
<https://doi.org/10.1016/B978-0-85709-523-7.00003-7>
- [4] Pandey G., Sreekumar M.: Development of high strength bio-composite material for light weight serial robot mechanisms. Procedia Computer Science, **76**, 512–521 (2015).
<https://doi.org/10.1016/j.procs.2015.12.328>
- [5] Chung D. D. L.: Polymer-matrix composites: Mechanical properties and thermal performance. in 'Carbon composites: Composites with carbon fibers, nanofibers and nanotubes' (ed.: Chung D. D. L.) Elsevier, Amsterdam, 218–255 (2017).
<https://doi.org/10.1016/B978-0-12-804459-9.00004-X>
- [6] Hussain F., Hojjati M., Okamoto M., Gorga R. E.: Polymer-matrix nanocomposites, processing, manufacturing, and application: An overview. Journal of Composite Materials, **40**, 1511–1575 (2006).
<https://doi.org/10.1177/0021998306067321>
- [7] Advani S. G., Hsiao K. T.: Manufacturing techniques for polymer matrix composites (PMCs). Elsevier, Amsterdam (2012).
- [8] Peters S. T.: Handbook of composites. Springer, New York (1998).
- [9] Singha A. S., Thakur V. K.: Mechanical properties of natural fibre reinforced polymer composites. Bulletin of Materials Science, **31**, 791–799 (2008).
<https://doi.org/10.1007/s12034-008-0126-x>
- [10] Jawaid M., Abdul Khalil H. P. S.: Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. Carbohydrate Polymers, **86**, 1–18 (2011).
<https://doi.org/10.1016/j.carbpol.2011.04.043>
- [11] Wu Y., Xia C., Cai L., Garcia A. C., Shi S. Q.: Development of natural fiber-reinforced composite with comparable mechanical properties and reduced energy consumption and environmental impacts for replacing automotive glass-fiber sheet molding compound. Journal of Cleaner Production, **184**, 92–100 (2018).
<https://doi.org/10.1016/j.jclepro.2018.02.257>
- [12] Bambach M. R.: Compression strength of natural fibre composite plates and sections of flax, jute and hemp. Thin-Walled Structures, **119**, 103–113 (2017).
<https://doi.org/10.1016/j.tws.2017.05.034>
- [13] Tian F., Zhong Z.: Modeling of load responses for natural fiber reinforced composites under water absorption. Composites Part A: Applied Science and Manufacturing, **125**, 105564/1–105564/31 (2019).
<https://doi.org/10.1016/j.compositesa.2019.105564>
- [14] Sarikaya E., Çallıoğlu H., Demirel H.: Production of epoxy composites reinforced by different natural fibers and their mechanical properties. Composites Part B: Engineering, **167**, 461–466 (2019).
<https://doi.org/10.1016/j.compositesb.2019.03.020>
- [15] Balla V. K., Kate K. H., Satyavolu J., Singh P., Tadimeti J. G. D.: Additive manufacturing of natural fiber reinforced polymer composites: Processing and prospects. Composites Part B: Engineering, **174**, 106956/1–106956/29 (2019).
<https://doi.org/10.1016/j.compositesb.2019.106956>
- [16] Holbery J., Houston D.: Natural-fiber-reinforced polymer composites in automotive applications. The Journal of the Minerals, Metals and Materials Society, **58**, 80–86 (2006).
<https://doi.org/10.1007/s11837-006-0234-2>
- [17] Alves C., Ferrão P. M. C., Silva A. J., Reis L. G., Freitas M., Rodrigues L. B., Alves D. E.: Ecodesign of automotive components making use of natural jute fiber composites. Journal of Cleaner Production, **18**, 313–327 (2010).
<https://doi.org/10.1016/j.jclepro.2009.10.022>
- [18] Cheung H.-Y., Ho M.-P., Lau K.-T., Cardona F., Hui D.: Natural fibre-reinforced composites for bioengineering and environmental engineering applications. Composites Part B: Engineering, **40**, 655–663 (2009).
<https://doi.org/10.1016/j.compositesb.2009.04.014>
- [19] Luzi F., Puglia D., Torre L.: Natural fiber biodegradable composites and nanocomposites: A biomedical application. in 'Biomass, biopolymer-based materials, and bioenergy' (eds.: Verma D., Fortunati E., Jain S., Zhang X.) Elsevier, Amsterdam, 179–201 (2017).
<https://doi.org/10.1016/B978-0-08-102426-3.00010-2>
- [20] Komuraiah A., Kumar N. S., Prasad B. D.: Chemical composition of natural fibers and its influence on their mechanical properties. Mechanics of Composite Materials, **50**, 359–376 (2014).
<https://doi.org/10.1007/s11029-014-9422-2>

- [21] Djafari Petroudy S. R.: Physical and mechanical properties of natural fibers. in 'Advanced high strength natural fibre composites in construction' (eds.: Fan M., Fu F.) Elsevier, Amsterdam, 59–83 (2017).
<https://doi.org/10.1016/B978-0-08-100411-1.00003-0>
- [22] Ali A., Shaker K., Nawab Y., Jabbar M., Hussain T., Militky J., Baheti V.: Hydrophobic treatment of natural fibers and their composites – A review. *Journal of Industrial Textiles*, **47**, 2153–2183 (2016).
<https://doi.org/10.1177/1528083716654468>
- [23] Grammatikos S. A., Zafari B., Evernden M. C., Mottram J. T., Mitchels J. M.: Moisture uptake characteristics of a pultruded fibre reinforced polymer flat sheet subjected to hot/wet aging. *Polymer Degradation and Stability*, **121**, 407–419 (2015).
<https://doi.org/10.1016/j.polymdegradstab.2015.10.001>
- [24] Sorieul M., Dickson A., Hill S., Pearson H.: Plant fibre: Molecular structure and biomechanical properties, of a complex living material, influencing its deconstruction towards a biobased composite. *Materials*, **9**, 618/1–618/36 (2016).
<https://doi.org/10.3390/ma9080618>
- [25] Nasrollahzadeh M., Sajjadi M., Sajadi S. M., Issaabadi Z.: Green nanotechnology. in 'Interface science and technology' (eds.: Kyzas G., Mitropoulos A.) Elsevier, Amsterdam, 145–198 (2019).
<https://doi.org/10.1016/B978-0-12-813586-0.00005-5>
- [26] Beg M. D. H., Mina M. F., Yunus R. M., Alam A. K. M. M.: The use of oil palm biomass (OPB) fibers as reinforcements in composites. in 'Biofiber reinforcements in composite materials' (eds.: Faruk O., Sain M.) Elsevier, Amsterdam, 342–382 (2015).
<https://doi.org/10.1533/9781782421276.3.342>
- [27] Ferreira D. P., Cruz J., Figueiro R.: Surface modification of natural fibers in polymer composites. in 'Green composites for automotive applications' (eds.: Georgios K., Arlindo S.) Elsevier, Amsterdam, 3–41 (2019).
<https://doi.org/10.1016/B978-0-08-102177-4.00001-X>
- [28] Faruk O., Bledzki A. K., Fink H-P., Sain M.: Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, **37**, 1552–1596 (2012).
<https://doi.org/10.1016/j.progpolymsci.2012.04.003>
- [29] Balakrishnan P., John M. J., Pothan L., Sreekala M. S., Thomas S.: Natural fibre and polymer matrix composites and their applications in aerospace engineering. in 'Advanced composite materials for aerospace engineering' (eds.: Rana S., Figueiro R.) Elsevier, Amsterdam, 365–383 (2016).
<https://doi.org/10.1016/B978-0-08-100037-3.00012-2>
- [30] Céline A., Fréour S., Jacquemin F., Casari P.: The hygroscopic behavior of plant fibers: A review. *Frontiers in Chemistry*, **1**, 43/1–43/12 (2014).
<https://doi.org/10.3389/fchem.2013.00043>
- [31] Osorio L., Trujillo E., van Vuure A. W., Verpoest I.: Morphological aspects and mechanical properties of single bamboo fibers and flexural characterization of bamboo/ epoxy composites. *Journal of Reinforced Plastics and Composites*, **30**, 396–408 (2011).
<https://doi.org/10.1177/0731684410397683>
- [32] Ansell M. P., Mwaikambo L. Y.: The structure of cotton and other plant fibres. in 'Handbook of textile fibre structure' (eds.: Eichhorn S. J., Hearle J. W. S., Jaffe M., Kikutani T.) Elsevier, Amsterdam, 62–94 (2009).
<https://doi.org/10.1533/9781845697310.1.62>
- [33] Haniffa M. A. C. M., Ching Y. C., Abdullah L. C., Poh S. C., Chuah C. H.: Review of bionanocomposite coating films and their applications. *Polymers*, **8**, 246/1–246/33 (2016).
<https://doi.org/10.3390/polym8070246>
- [34] Khan M. Z. R., Srivastava S. K., Gupta M. K.: Tensile and flexural properties of natural fiber reinforced polymer composites: A review. *Journal of Reinforced Plastics and Composites*, **37**, 1435–1455 (2018).
<https://doi.org/10.1177/0731684418799528>
- [35] Taib M. N. A. M., Julkapli N. M.: Dimensional stability of natural fiber-based and hybrid composites. in 'Mechanical and physical testing of biocomposites, fibre-reinforced composites and hybrid composites' (eds.: Jawaid M., Thariq M., Saba N.) Elsevier, Amsterdam, 61–79 (2019).
<https://doi.org/10.1016/B978-0-08-102292-4.00004-7>
- [36] Wang W., Sain M., Cooper P.: Study of moisture absorption in natural fiber plastic composites. *Composites Science and Technology*, **66**, 379–386 (2006).
<https://doi.org/10.1016/j.compscitech.2005.07.027>
- [37] Laftah W. A., Hashim S.: The influence of plant natural fibers on swelling behavior of polymer hydrogels. *Journal of Composite Materials*, **48**, 555–569 (2013).
<https://doi.org/10.1177/0021998313476323>
- [38] Monteiro S. N., Calado V., Rodriguez R. J. S., Margem F. M.: Thermogravimetric behavior of natural fibers reinforced polymer composites – An overview. *Materials Science and Engineering: A*, **557**, 17–28 (2012).
<https://doi.org/10.1016/j.msea.2012.05.109>
- [39] Fiore V., Scalici T., Nicoletti F., Vitale G., Prestipino M., Valenza A.: A new eco-friendly chemical treatment of natural fibres: Effect of sodium bicarbonate on properties of sisal fibre and its epoxy composites. *Composites Part B: Engineering*, **85**, 150–160 (2016).
<http://doi.org/10.1016/j.compositesb.2015.09.028>
- [40] Adekunle K. F.: Surface treatments of natural fibres – A review: Part 1. *Open Journal of Polymer Chemistry*, **05**, 41–46 (2015).
<https://doi.org/10.4236/ojpcchem.2015.53005>
- [41] Koohestani B., Darban A. K., Mokhtari P., Yilmaz E., Darezereshki E.: Comparison of different natural fiber treatments: A literature review. *International Journal of Environmental Science and Technology*, **16**, 629–642 (2018).
<https://doi.org/10.1007/s13762-018-1890-9>

- [42] Cruz J., Figueiro R.: Surface modification of natural fibers: A review. *Procedia Engineering*, **155**, 285–288 (2016).
<https://doi.org/10.1016/j.proeng.2016.08.030>
- [43] Al-Maharma A. Y., Al-Huniti N.: Critical review of the parameters affecting the effectiveness of moisture absorption treatments used for natural composites. *Journal of Composite Science*, **3**, 27/1–27/38 (2019).
<https://doi.org/10.3390/jcs3010027>
- [44] Chen H., Zhang W., Wang X., Wang H., Wu Y., Zhong T., Fei B.: Effect of alkali treatment on wettability and thermal stability of individual bamboo fibers. *Journal of Wood Science*, **64**, 398–405 (2018).
<https://doi.org/10.1007/s10086-018-1713-0>
- [45] Edeerozey A. M. M., Akil H. M., Azhar A. B., Ariffin M. I. Z.: Chemical modification of kenaf fibers. *Materials Letters*, **61**, 2023–2025 (2007).
<https://doi.org/10.1016/j.matlet.2006.08.006>
- [46] Mwaikambo L. Y., Ansell M. P.: Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization. *Journal of Applied Polymer Science*, **84**, 2222–2234 (2002).
<https://doi.org/10.1002/app.10460>
- [47] Bujjibabu G., Das V. C., Ramakrishna M., Nagarjuna K.: Mechanical and water absorption behavior of natural fibers reinforced polypropylene hybrid composites. *Materials Today: Proceedings*, **5**, 12249–12256 (2018).
<https://doi.org/10.1016/j.matpr.2018.02.202>
- [48] Jasbi M. S., Hasani H., Zadhoush A., Safi S.: Effect of alkali treatment on mechanical properties of the green composites reinforced with milkweed fibers. *The Journal of The Textile Institute*, **109**, 24–31 (2017).
<https://doi.org/10.1080/00405000.2017.1320816>
- [49] Fahim M., Chand N.: *Tribology of natural fiber polymer composites*. Elsevier, Amsterdam (2008).
- [50] Xie Y., Hill C. A. S., Xiao Z., Militz H., Mai C.: Silane coupling agents used for natural fiber/polymer composites: A review. *Composites Part A: Applied Science and Manufacturing*, **41**, 806–819 (2010).
<https://doi.org/10.1016/j.compositesa.2010.03.005>
- [51] Seki Y.: Innovative multifunctional siloxane treatment of jute fiber surface and its effect on the mechanical properties of jute/thermoset composites. *Materials Science and Engineering: A*, **508**, 247–252 (2009).
<https://doi.org/10.1016/j.msea.2009.01.043>
- [52] Liu Y., Lv X., Bao J., Xie J., Tang X., Che J., Ma Y., Tong J.: Characterization of silane treated and untreated natural cellulosic fibre from corn stalk waste as potential reinforcement in polymer composites. *Carbohydrate Polymers*, **218**, 179–187 (2019).
<https://doi.org/10.1016/j.carbpol.2019.04.088>
- [53] Bledzki A. K., Mamun A. A., Lucka-Gabor M., Gutowski V. S.: The effects of acetylation on properties of flax fibre and its polypropylene composites. *Express Polymer Letters*, **2**, 413–422 (2008).
<https://doi.org/10.3144/expresspolymlett.2008.50>
- [54] Tserki V., Zafeiropoulos N. E., Simon F., Panayiotou C.: A study of the effect of acetylation and propionylation surface treatments on natural fibres. *Composites Part A: Applied Science and Manufacturing*, **36**, 1110–1118 (2005).
<https://doi.org/10.1016/j.compositesa.2005.01.004>
- [55] Zaman H. U., Khan R. A.: Acetylation used for natural fiber/polymer composites. *Journal of Thermoplastic Composite Materials*, in press (2019).
<https://doi.org/10.1177/0892705719838000>
- [56] Karaduman Y., Ozdemir H., Karaduman N. S. Ozdemir G.: Interfacial modification of hemp fiber–reinforced composites. in ‘Natural and artificial fiber-reinforced composites as renewable sources’ (ed.: Günay E.) IntechOpen, London, 17–39 (2018).
<https://doi.org/10.5772/intechopen.70519>
- [57] Joseph K., Thomas S., Pavithran C.: Effect of chemical treatment on the tensile properties of short sisal fibre-reinforced polyethylene composites. *Polymer*, **37**, 5139–5149 (1996).
[https://doi.org/10.1016/0032-3861\(96\)00144-9](https://doi.org/10.1016/0032-3861(96)00144-9)
- [58] Ahmad E. E. M., Luyt A. S.: Effects of organic peroxide and polymer chain structure on morphology and thermal properties of sisal fibre reinforced polyethylene composites. *Composites Part A: Applied Science and Manufacturing*, **43**, 703–710 (2012).
<https://doi.org/10.1016/j.compositesa.2011.12.011>
- [59] Mohanty A. K., Misra M., Drzal L. T.: Surface modifications of natural fibers and performance of the resulting biocomposites: An overview. *Composite Interfaces*, **8**, 313–343 (2001).
<https://doi.org/10.1163/156855401753255422>
- [60] Sari N. H., Sanjay M. R., Arpitha G. R., Pruncu C. I., Siengchin S.: Synthesis and properties of pandanwangi fiber reinforced polyethylene composites: Evaluation of dicumyl peroxide (DCP) effect. *Composites Communications*, **15**, 53–57 (2019).
<https://doi.org/10.1016/j.coco.2019.06.007>
- [61] Jha V., Kataria V., Verma J., Pradhan S.: Potential biodegradable matrices and fiber treatment for green composites: A review. *AIMS Materials Science*, **6**, 119–138 (2019).
<https://doi.org/10.3934/matricsci.2019.1.119>
- [62] El-Shekeil Y. A., Sapuan S. M., Khalina A., Zainudin E. S., Al-Shuja’a O. M.: Influence of chemical treatment on the tensile properties of kenaf fiber reinforced thermoplastic polyurethane composite. *Express Polymer Letters*, **6**, 1032–1040 (2012).
<https://doi.org/10.3144/expresspolymlett.2012.108>
- [63] Arjmand F., Barmar M., Barikani M.: Isocyanate modification of wood fiber in enhancing the performance of its composites with high density polyethylene. *Polymers from Renewable Resources*, **3**, 43–60 (2012).
<https://doi.org/10.1177/204124791200300202>

- [64] Rozman H. D., Ahmad Hilme K. R., Abubakar A.: Polyurethane composites based on oil palm empty fruit bunches: Effect of isocyanate/hydroxyl ratio and chemical modification of empty fruit bunches with toluene diisocyanate and hexamethylene diisocyanate on mechanical properties. *Journal of Applied Polymer Science*, **106**, 2290–2297 (2007).
<https://doi.org/10.1002/app.25119>
- [65] Sair S., Oushabi A., Kammouni A., Tanane O., Abboud Y., El Bouari A.: Mechanical and thermal conductivity properties of hemp fiber reinforced polyurethane composites. *Case Studies in Construction Materials*, **8**, 203–212 (2018).
<https://doi.org/10.1016/j.cscm.2018.02.001>
- [66] Tayfun U., Dogan M., Bayramli E.: Investigations of the flax fiber/thermoplastic polyurethane eco-composites: Influence of isocyanate modification of flax fiber surface. *Polymer Composites*, **38**, 2874–2880 (2017).
<https://doi.org/10.1002/pc.23889>
- [67] Kabir M. M., Wang H., Lau K., Cardona F.: Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. *Composites Part B: Engineering*, **43**, 2883–2892 (2012).
<https://doi.org/10.1016/j.compositesb.2012.04.053>
- [68] Kono H.: Preparation and characterization of amphoteric cellulose hydrogels as adsorbents for the anionic dyes in aqueous solutions. *Gels*, **1**, 94–116 (2015).
<https://doi.org/10.3390/gels1010094>
- [69] Acharya S., Abidi N., Rajbhandari R., Meulewaeter F.: Chemical cationization of cotton fabric for improved dye uptake. *Cellulose*, **21**, 4693–4706 (2014).
<https://doi.org/10.1007/s10570-014-0457-2>
- [70] Shateri Khalil-Abad M., Yazdanshenas M. E., Nateghi M. R.: Effect of cationization on adsorption of silver nanoparticles on cotton surfaces and its antibacterial activity. *Cellulose*, **16**, 1147–1157 (2009).
<https://doi.org/10.1007/s10570-009-9351-8>
- [71] Parvinzadeh Gashti M., Elahi A., Parvinzadeh Gashti M.: UV radiation inducing succinic acid/silica-kaolinite network on cellulose fiber to improve the functionality. *Composites Part B: Engineering*, **48**, 158–166 (2013).
<https://doi.org/10.1016/j.compositesb.2012.12.002>
- [72] Alimohammadi F., Parvinzadeh Gashti M., Shamei A.: Functional cellulose fibers via polycarboxylic acid/carbon nanotube composite coating. *Journal of Coatings Technology and Research*, **10**, 123–132 (2012).
<https://doi.org/10.1007/s11998-012-9429-3>
- [73] Gashti M. P., Eslami S.: A robust method for producing electromagnetic shielding cellulose via iron oxide pillared clay coating under ultraviolet irradiation. *Functional Materials Letters*, **08**, 1550073/1–1550073/4 (2015).
<https://doi.org/10.1142/s1793604715500733>
- [74] Alimohammadi F., Gashti M. P., Shamei A.: A novel method for coating of carbon nanotube on cellulose fiber using 1,2,3,4-butanetetracarboxylic acid as a cross-linking agent. *Progress in Organic Coatings*, **74**, 470–478 (2012).
<https://doi.org/10.1016/j.porgcoat.2012.01.012>
- [75] Gashti M. P., Alimohammadi F., Shamei A.: Preparation of water-repellent cellulose fibers using a polycarboxylic acid/hydrophobic silica nanocomposite coating. *Surface and Coatings Technology*, **206**, 3208–3215 (2012).
<https://doi.org/10.1016/j.surfcoat.2012.01.006>
- [76] Sehaqui H., Kulasinski K., Pfenninger N., Zimmermann T., Tingaut P.: Highly carboxylated cellulose nanofibers via succinic anhydride esterification of wheat fibers and facile mechanical disintegration. *Biomacromolecules*, **18**, 242–248 (2016).
<https://doi.org/10.1021/acs.biomac.6b01548>
- [77] Voit B., Böhme F., Adler H. J. P.: *Synthesis of defined polymer architectures*. Wiley, Weinheim (2002).
- [78] Parvinzadeh Gashti M., Almasian A.: UV radiation induced flame retardant cellulose fiber by using polyvinylphosphonic acid/carbon nanotube composite coating. *Composites Part B: Engineering*, **45**, 282–289 (2013).
<https://doi.org/10.1016/j.compositesb.2012.07.052>
- [79] Nooralian Z., Parvinzadeh Gashti M., Ebrahimi I.: Fabrication of a multifunctional graphene/polyvinylphosphonic acid/cotton nanocomposite via facile spray layer-by-layer assembly. *RSC Advances*, **6**, 23288–23299 (2016).
<https://doi.org/10.1039/c6ra00296j>
- [80] El-Shafei A. M., Adel A. M., Ibrahim A. A., Al-Shemy M. T.: Dual functional jute fabric biocomposite with chitosan and phosphorylated nano-cellulose (antimicrobial and thermal stability). *International Journal of Biological Macromolecules*, **124**, 733–741 (2019).
<https://doi.org/10.1016/j.ijbiomac.2018.11.137>
- [81] Tzanov T., Stamenova M., Cavaco-Paulo A.: Phosphorylation of cotton cellulose with Baker's yeast hexokinase. *Macromolecular Rapid Communications*, **23**, 962–964 (2002).
[https://doi.org/10.1002/1521-3927\(200211\)23:16<962::AID-MARC962>3.0.CO;2-B](https://doi.org/10.1002/1521-3927(200211)23:16<962::AID-MARC962>3.0.CO;2-B)
- [82] Pan H., Song L., Ma L., Pan Y., Liew K. M., Hu Y.: Layer-by-layer assembled thin films based on fully biobased polysaccharides: Chitosan and phosphorylated cellulose for flame-retardant cotton fabric. *Cellulose*, **21**, 2995–3006 (2014).
<https://doi.org/10.1007/s10570-014-0276-5>
- [83] Heo J., Choi D., Hong J.: Layer-by-layer self-assembled ferrite multilayer nanofilms for microwave absorption. *Journal of Nanomaterials*, **2015**, 164619/1–164619/8 (2015).
<https://doi.org/10.1155/2015/164619>

- [84] Li Z., Liu B., Kong H., Yu M., Qin M., Teng C.: Layer-by-layer self-assembly strategy for surface modification of aramid fibers to enhance interfacial adhesion to epoxy resin. *Polymers*, **10**, 820/1–820/14 (2018).
<https://doi.org/10.3390/polym10080820>
- [85] Battegazzore D., Frache A., Carosio F.: Sustainable and high performing biocomposites with chitosan/sepiolite layer-by-layer nanoengineered interphases. *ACS Sustainable Chemistry and Engineering*, **6**, 9601–9605 (2018).
<https://doi.org/10.1021/acssuschemeng.8b02907>
- [86] Li H., Fu S., Peng L., Zhan H.: Surface modification of cellulose fibers with layer-by-layer self-assembly of lignosulfonate and polyelectrolyte: Effects on fibers wetting properties and paper strength. *Cellulose*, **19**, 533–546 (2012).
<https://doi.org/10.1007/s10570-011-9639-3>
- [87] Wei C., Zeng S., Tan Y., Wang W., Lv J., Liu H.: Impact of layer-by-layer self-assembly clay-based nano-coating on flame retardant properties of sisal fiber cellulose microcrystals. *Advances in Materials Science and Engineering*, **2015**, 691290/1–691290/7 (2015).
<https://doi.org/10.1155/2015/691290>
- [88] González J. T. C., Dillon A. J. P., Pérez-Pérez A. R., Fontana R., Bergmann C. P.: Enzymatic surface modification of sisal fibers (*Agave sisalana*) by *Penicillium echinulatum* cellulases. *Fibers and Polymers*, **16**, 2112–2120 (2015).
<https://doi.org/10.1007/s12221-015-4705-3>
- [89] Höcker H.: Plasma treatment of textile fibers. *Pure and Applied Chemistry*, **74**, 423–427 (2002).
<https://doi.org/10.1351/pac200274030423>
- [90] Valášek P., Müller M., Šleger V.: Influence of plasma treatment on mechanical properties of cellulose-based fibres and their interfacial interaction in composite systems. *BioResources*, **12**, 5449–5461 (2017).
<https://doi.org/10.15376/biores.12.3.5449-5461>
- [91] Tafti H. R. G., Valipour P., Mirjali M.: Effects of corona treatment on morphology and properties of carbon based fillers/epoxy nanocomposites. *Polymer Composites*, **39**, 2298–2304 (2018).
<https://doi.org/10.1002/pc.24622>
- [92] Zheng Z., Wang X., Huang X., Shi M., Zhou G.: Chemical modification combined with corona treatment of UHMWPE fibers and their adhesion to vinyl-ester resin. *Journal of Adhesion Science and Technology*, **20**, 1047–1059 (2006).
<https://doi.org/10.1163/15685610677890626>
- [93] Gashti M. P., Pournaserani A., Ehsani H., Gashti M. P.: Surface oxidation of cellulose by ozone-gas in a vacuum cylinder to improve the functionality of fluoromonomer. *Vacuum*, **91**, 7–13 (2013).
<https://doi.org/10.1016/j.vacuum.2012.10.015>
- [94] Elanchezhian C., Ramnath B. V., Ramakrishnan G., Rajendrakumar M., Naveenkumar V., Saravanakumar M. K.: Review on mechanical properties of natural fiber composites. *Materials Today: Proceedings*, **5**, 1785–1790 (2018).
<https://doi.org/10.1016/j.matpr.2017.11.276>
- [95] Pouyet F., Chirat C., Potthast A., Lachenal D.: Formation of carbonyl groups on cellulose during ozone treatment of pulp: Consequences for pulp bleaching. *Carbohydrate Polymers*, **109**, 85–91 (2014).
<https://doi.org/10.1016/j.carbpol.2014.02.082>
- [96] Eren H. A., Avinc O., Uysal P., Wilding M.: The effects of ozone treatment on polylactic acid (PLA) fibres. *Textile Research Journal*, **81**, 1091–1099 (2011).
<https://doi.org/10.1177/0040517510397576>
- [97] Sargunamani D., Selvakumar N.: Effects of ozone treatment on the properties of raw and degummed tassar silk fabrics. *Journal of Applied Polymer Science*, **104**, 147–155 (2007).
<https://doi.org/10.1002/app.24761>
- [98] Maqsood H. S., Bashir U., Wiener J., Puchalski M., Sztajnowski S., Militky J.: Ozone treatment of jute fibers. *Cellulose*, **24**, 1543–1553 (2017).
<https://doi.org/10.1007/s10570-016-1164-y>
- [99] Asim M., Abdan K., Jawaid M., Nasir M., Dashtizadeh Z., Ishak M. R., Hoque M. E.: A review on pineapple leaves fibre and its composites. *International Journal of Polymer Science*, **1**, 950567/1–950567/16 (2015).
<https://doi.org/10.1155/2015/950567>
- [100] Laftah W. A., Rahman W. A. W. A.: Pulping process and the potential of using non-wood pineapple leaves fiber for pulp and paper production: A review. *Journal of Natural Fibers*, **13**, 85–101 (2016).
<https://doi.org/10.1080/15440478.2014.984060>
- [101] Debnath S.: Pineapple leaf fibre – A sustainable luxury and industrial textiles. in ‘Handbook of sustainable luxury textiles and fashion’ (eds.: Gardetti M. A., Muthu S. S.) Springer, Singapore, 35–49 (2016).
https://doi.org/10.1007/978-981-287-742-0_3
- [102] Uddin N., Miah S., Jalil M., Islam M., Siddika A.: A review on extraction, characterization and application of pineapple leaf fiber (PALF) in textiles and other fields. *International Journal of Advanced Research*, **5**, 112–116 (2017).
<https://doi.org/10.21474/ijar01/3786>
- [103] Yusof Y., Ahmad M. R., Saidin W., Mustapa M. S., Tahar M. S.: Producing paper using pineapple leaf fiber. *Advanced Materials Research*, **383**, 3382–3386 (2011).
<https://doi.org/10.4028/www.scientific.net/AMR.383-390.3382>
- [104] Gardetti M. A., Muthu S. S.: Handbook of sustainable luxury textiles and fashion. Springer, Singapore (2015).

- [105] Leão A. L., Cherian B. M., Narine S., Souza S. F., Sain M., Thomas S.: The use of pineapple leaf fibers (PALFs) as reinforcements in composites. in 'Biofiber reinforcements in composite materials' (eds.: Omar F., Mohini S.) Elsevier, Amsterdam, 211–235 (2015).
<https://doi.org/10.1533/9781782421276.2.211>
- [106] Mishra S., Misra M., Tripathy S. S., Nayak S. K., Mohanty A. K.: Potentiality of pineapple leaf fibre as reinforcement in PALF-polyester composite: Surface modification and mechanical performance. *Journal of Reinforced Plastics and Composites*, **20**, 321–334 (2016).
<https://doi.org/10.1177/073168401772678779>
- [107] Mishra S., Mohanty A. K., Drzal L. T., Misra M., Hinrichsen G.: A review on pineapple leaf fibers, sisal fibers and their biocomposites. *Macromolecular Materials and Engineering*, **289**, 955–974 (2004).
<https://doi.org/10.1002/mame.200400132>
- [108] Kengkhetkit N., Amornsakchai T.: Utilisation of pineapple leaf waste for plastic reinforcement: 1. A novel extraction method for short pineapple leaf fiber. *Industrial Crops and Products*, **40**, 55–61 (2012).
<https://doi.org/10.1016/j.indcrop.2012.02.037>
- [109] Hulle A., Kadole P., Katkar P.: Agave americana leaf fibers. *Fibers*, **3**, 64–75 (2015).
<https://doi.org/10.3390/fib3010064>
- [110] Cueto C. U., Quintos A. G., Peralta C. N., Palmario M. S.: Pineapple fibers. The retting process. II. *Technology Journal*, **1**, 73–79 (1978).
- [111] Desai A. J., Chovatiya A. B., Ghoniya H. R.: Design and development of raspador machine. *International Journal of Scientific Research and Review*, **7**, 46–54 (2018).
- [112] Banik S., Nag D., Dehnath S.: Utilization of pineapple leaf agro-waste for extraction of fibre and the residual biomass for vermicomposting. *Indian Journal of Fibre and Textile Research*, **36**, 172–177 (2011).
- [113] Sreenivasan V. S., Somasundaram S., Ravindran D., Manikandan V., Narayanasamy R.: Microstructural, physico-chemical and mechanical characterisation of *Sansevieria cylindrica* fibres – An exploratory investigation. *Materials and Design*, **32**, 453–461 (2011).
<https://doi.org/10.1016/j.matdes.2010.06.004>
- [114] Yusof Y., Yahya S. A., Adam A.: Novel technology for sustainable pineapple leaf fibers productions. *Procedia CIRP*, **26**, 756–760 (2015).
<https://doi.org/10.1016/j.procir.2014.07.160>
- [115] Jaya Vinse Ruban Y., Ginil Mon S., Vetha Roy D.: Chemical resistance/thermal and mechanical properties of unsaturated polyester-based nanocomposites. *Applied Nanoscience*, **4**, 233–240 (2013).
<https://doi.org/10.1007/s13204-013-0193-1>
- [116] Rusmirović J. D., Trifković K. T., Bugarski B., Pavlović V. B., Džunuzović J., Tomić M., Marinković A. D.: High performance unsaturated polyester based nanocomposites: Effect of vinyl modified nanosilica on mechanical properties. *Express Polymer Letters*, **10**, 139–159 (2016).
<https://doi.org/10.3144/expresspolymlett.2016.14>
- [117] Athijayamani A., Thiruchitrabalam M., Manikandan V., Pazhanivel B.: Mechanical properties of natural fibers reinforced polyester hybrid composite. *International Journal of Plastics Technology*, **14**, 104–116 (2010).
<https://doi.org/10.1007/s12588-009-0016-0>
- [118] Siregar J. P., Cionita T., Bachtiar D., Rejab M. R. M.: Tensile properties of pineapple leaf fibre reinforced unsaturated polyester composites. *Applied Mechanics and Materials*, **695**, 159–162 (2014).
<https://doi.org/10.4028/www.scientific.net/AMM.695.159>
- [119] Devi L. U., Bhagawan S. S., Thomas S.: Mechanical properties of pineapple leaf fiber-reinforced polyester composites. *Journal of Applied Polymer Science*, **64**, 1739–1748 (1997).
[https://doi.org/10.1002/\(SICI\)1097-4628\(19970531\)64:9<1739::AID-APP10>3.0.CO;2-T](https://doi.org/10.1002/(SICI)1097-4628(19970531)64:9<1739::AID-APP10>3.0.CO;2-T)
- [120] Juraidi J. M., Shuhairul N., Azuan S. A. S., Anuar N. I. S.: A comparison of tensile properties of polyester composites reinforced with pineapple leaf fiber and pineapple peduncle fiber. *IOP Conference Series: Materials Science and Engineering*, **50**, 1–6 (2013).
<https://doi.org/10.1088/1757-899X/50/1/012071>
- [121] Senthilkumar K., Saba N., Chandrasekar M., Jawaidd M., Rajini N., Alothman O. Y., Siengchin S.: Evaluation of mechanical and free vibration properties of the pineapple leaf fibre reinforced polyester composites. *Construction and Building Materials*, **195**, 423–431 (2019).
<https://doi.org/10.1016/j.conbuildmat.2018.11.081>
- [122] Daramola O. O., Adediran A. A., Adewuyi B. O., Adewole O.: Mechanical properties and water absorption behaviour of treated pineapple leaf fibre reinforced polyester matrix composites. *Leonardo Journal of Sciences*, **30**, 15–30 (2017).
- [123] Glória G. O., Teles M. C. A., Lopes F. P. D., Vieira C. M. F., Margem F. M., Gomes M. D. A., Monteiro S. N.: Tensile strength of polyester composites reinforced with PALF. *Journal of Materials Research and Technology*, **6**, 401–405 (2017).
<https://doi.org/10.1016/j.jmrt.2017.08.006>
- [124] Senthilkumar K., Muthukumar C., Nagarajan R., Thiagamani S. M. K., Saba N., Jawaidd M., Siengchin S., Ayrilmis N.: Effect of fibre loading and Ca(OH)₂ treatment on thermal, mechanical, and physical properties of pineapple leaf fibre/polyester reinforced composites. *Materials Research Express*, **6**, 1–15 (2019).
<https://doi.org/10.1088/2053-1591/ab2702>

- [125] Devi L. U., Bhagawan S. S., Thomas S.: Dynamic mechanical properties of pineapple leaf fiber polyester composites. *Polymer Composites*, **32**, 1741–1750 (2011).
<https://doi.org/10.1002/pc.21197>
- [126] Graupner N., Labonte D., Müssig J.: Rhubarb petioles inspire biodegradable cellulose fibre-reinforced PLA composites with increased impact strength. *Composites Part A: Applied Science and Manufacturing*, **98**, 218–226 (2017).
<https://doi.org/10.1016/j.compositesa.2017.03.021>
- [127] Easwara Prasad G. L., Keerthi Gowda B. S., Velmugan R.: A study on impact strength characteristics of coir polyester composites. *Procedia Engineering*, **173**, 771–777 (2017).
<https://doi.org/10.1016/j.proeng.2016.12.091>
- [128] Mathew L., Paul M. M.: Mechanical properties of pineapple fibre reinforced concrete subjected to high temperature. *GRD Journals – Global Research and Development Journal for Engineering*, **2**, 1–6 (2017).
- [129] Motaleb K. Z. M. A., Islam M. S., Hoque M. B.: Improvement of physicomaterial properties of pineapple leaf fiber reinforced composite. *International Journal of Biomaterials*, **7**, 1–7 (2018).
<https://doi.org/10.1155/2018/7384360>
- [130] Odusote J. K., Oyewo A. T.: Mechanical properties of pineapple leaf fibre reinforced polymer composites for application as prosthetic socket. *Journal of Engineering and Technology*, **7**, 125–139 (2016).
<https://doi.org/10.21859/jet-06011>
- [131] Devi L. U., Joseph K., Nair K. C. M., Thomas S.: Ageing studies of pineapple leaf fiber-reinforced polyester composites. *Journal of Applied Polymer Science*, **94**, 503–510 (2004).
<https://doi.org/10.1002/app.20924>
- [132] George J., Bhagawan S. S., Thomas S.: Effects of environment on the properties of low-density polyethylene composites reinforced with pineapple-leaf fibre. *Composites Science and Technology*, **58**, 1471–1485 (1998).
[https://doi.org/10.1016/s0266-3538\(97\)00161-9](https://doi.org/10.1016/s0266-3538(97)00161-9)
- [133] George J., Joseph K., Bhagawan S. S., Thomas S.: Influence of short pineapple fiber on the viscoelastic properties of low-density polyethylene. *Materials Letters*, **18**, 163–170 (1993).
[https://doi.org/10.1016/0167-577x\(93\)90119-i](https://doi.org/10.1016/0167-577x(93)90119-i)
- [134] George J., Bhagawan S. S., Thomas S.: Thermogravimetric and dynamic mechanical thermal analysis of pineapple fibre reinforced polyethylene composites. *Journal of Thermal Analysis*, **47**, 1121–1140 (1996).
<https://doi.org/10.1007/BF01979452>
- [135] Bahra M. S., Gupta V. K., Aggarwal L.: Effect of fibre content on mechanical properties and water absorption behaviour of pineapple/HDPE composite. *Materials Today: Proceedings*, **4**, 3207–3214 (2017).
<https://doi.org/10.1016/j.matpr.2017.02.206>
- [136] Kasim A. N., Selamat M. Z., Aznan N., Sahadan S. N., Daud M. A. M., Jumaidin R., Salleh S.: Effect of pineapple leaf fiber loading on the mechanical properties of pineapple leaf fiber – polypropylene composite. *Jurnal Teknologi*, **77**, 117–123 (2015).
<https://doi.org/10.11113/jt.v77.6617>
- [137] Hoque M. B., Solaiman, Alam A. B. M. H., Mahmud H., Nobi A.: Mechanical, degradation and water uptake properties of fabric reinforced polypropylene based composites: Effect of alkali on composites. *Fibers*, **6**, 94/1–94/10 (2018).
<https://doi.org/10.3390/fib6040094>
- [138] Berzin F., Amornsakchai T., Lemaitre A., Di Giuseppe E., Vergnes B.: Processing and properties of pineapple leaf fibers-polypropylene composites prepared by twin-screw extrusion. *Polymer Composites*, **39**, 4115–4122 (2018).
<https://doi.org/10.1002/pc.24475>
- [139] Rahman M. R., Huque M. M., Islam M. N., Hasan M.: Improvement of physico-mechanical properties of jute fiber reinforced polypropylene composites by post-treatment. *Composites Part A: Applied Science and Manufacturing*, **39**, 1739–1747 (2008).
<https://doi.org/10.1016/j.compositesa.2008.08.002>
- [140] Maleque M. A., Belal F. Y., Sapuan S. M.: Mechanical properties study of pseudo-stem banana fiber reinforced epoxy composite. *Arabian Journal for Science and Engineering*, **32**, 359–364 (2007).
- [141] Boopalan M., Niranjana M., Umapathy M. J.: Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites. *Composites Part B: Engineering*, **51**, 54–57 (2013).
<https://doi.org/10.1016/j.compositesb.2013.02.033>
- [142] Chattopadhyay S. K., Khandal R. K., Uppaluri R., Ghoshal A. K.: Influence of varying fiber lengths on mechanical, thermal, and morphological properties of MA-g-PP compatibilized and chemically modified short pineapple leaf fiber reinforced polypropylene composites. *Journal of Applied Polymer Science*, **113**, 3750–3756 (2009).
<https://doi.org/10.1002/app.30252>
- [143] Munawar R. F., Jamil N. H., Shahril M. K., Skh Abdul Rahim S. M., Zainal Abidin M. Z., Azam M. A., Lau K. T.: Development of green composite: Pineapple leaf fibers (PALF) reinforced polylactide (PLA). *Applied Mechanics and Materials*, **761**, 520–525 (2015).
<https://doi.org/10.4028/www.scientific.net/AMM.761.520>
- [144] Kaewpirom S., Worrarat C.: Preparation and properties of pineapple leaf fiber reinforced poly(lactic acid) green composites. *Fibers and Polymers*, **15**, 1469–1477 (2014).
<https://doi.org/10.1007/s12221-014-1469-0>

- [145] Huda M. S., Drzal L. T., Mohanty A. K., Misra M.: Effect of chemical modifications of the pineapple leaf fiber surfaces on the interfacial and mechanical properties of laminated biocomposites. *Composite Interfaces*, **15**, 169–191 (2012).
<https://doi.org/10.1163/156855408783810920>
- [146] Agung E. H., Hamdan M. H. M., Siregar J. P., Bachtiar D., Tezara C., Jamiluddin J.: Water absorption behaviour and mechanical performance of pineapple leaf fibre reinforced polylactic acid composites. *International Journal of Automotive and Mechanical Engineering*, **15**, 5760–5774 (2018).
<https://doi.org/10.15282/ijame.15.4.2018.4.0441>
- [147] Zin M. H., Abdan K., Norizan M. N.: The effect of different fiber loading on flexural and thermal properties of banana/pineapple leaf (PALF)/glass hybrid composite. in ‘Structural health monitoring of biocomposites, fibre-reinforced composites and hybrid composites’ (eds.: Jawaid M., Thariq M., Saba N.) Elsevier, Amsterdam, 1–17 (2019).
<https://doi.org/10.1016/B978-0-08-102291-7.00001-0>
- [148] Das S., Rahman M., Hasan M.: Physico-mechanical properties of pineapple leaf and banana fiber reinforced hybrid polypropylene composites: Effect of fiber ratio and sodium hydroxide treatment. *IOP Conference Series: Materials Science and Engineering*, **438**, 012027/1–012027/8 (2018).
<https://doi.org/10.1088/1757-899X/438/1/012027>
- [149] Shih Y-F., Chang W-C., Liu W-C., Lee C-C., Kuan C-S., Yu Y-H.: Pineapple leaf/recycled disposable chopstick hybrid fiber-reinforced biodegradable composites. *Journal of the Taiwan Institute of Chemical Engineers*, **45**, 2039–2046 (2014).
<https://doi.org/10.1016/j.jtice.2014.02.015>
- [150] Yogesh M., Rao A. N. H.: Fabrication, mechanical characterization of pineapple leaf fiber (PALF) reinforced vinyl ester hybrid composites. *AIP Conference Proceedings*, **1943**, 020062/1–020062/12 (2018).
<https://doi.org/10.1063/1.5029638>
- [151] Asim M., Jawaid M., Abdan K., Ishak M. R.: Effect of pineapple leaf fibre and kenaf fibre treatment on mechanical performance of phenolic hybrid composites. *Fibers and Polymers*, **18**, 940–947 (2017).
<https://doi.org/10.1007/s12221-017-1236-0>
- [152] Rahman M., Das S., Hasan M.: Mechanical properties of chemically treated banana and pineapple leaf fiber reinforced hybrid polypropylene composites. *Advances in Materials and Processing Technologies*, **4**, 527–537 (2018).
<https://doi.org/10.1080/2374068X.2018.1468972>
- [153] Mazalan M. F., Yusof Y.: Natural pineapple leaf fibre extraction on Josapine and Morris. in ‘8th International Conference on Mechanical and Manufacturing Engineering – (ICME’17) Langkawi, Malaysia’ Vol 135, 00043/1–00043/6 (2017).
<https://doi.org/10.1051/mateconf/201713500043>
- [154] Li Y., Mai Y-W., Ye L.: Sisal fibre and its composites: A review of recent developments. *Composites Science and Technology*, **60**, 2037–2055 (2000).
[https://doi.org/10.1016/S0266-3538\(00\)00101-9](https://doi.org/10.1016/S0266-3538(00)00101-9)
- [155] Yu C.: Sisal. in ‘Bast and other plant fibres’ (ed.: Franck R. E.) Elsevier, Amsterdam, 228–273 (2005).
<https://doi.org/10.1533/9781845690618.228>
- [156] Chand N., Fahim M.: Sisal reinforced polymer composites. in ‘Tribology of natural fiber polymer composites’ (eds.: Chand N., Fahim M.) Elsevier, Amsterdam, 84–107 (2008).
<https://doi.org/10.1533/9781845695057.84>
- [157] Bisanda E. T. N., Ansell M. P.: Properties of sisal-CNSL composites. *Journal of Materials Science*, **27**, 1690–1700 (1992).
<https://doi.org/10.1007/BF00542934>
- [158] Kumar P. K., Sekaran A. S. J.: Some natural fibers used in polymer composites and their extraction processes: A review. *Journal of Reinforced Plastics and Composites*, **33**, 1879–1892 (2014).
<https://doi.org/10.1177/0731684414548612>
- [159] Sreekumar P. A., Joseph K., Unnikrishnan G., Thomas S.: A comparative study on mechanical properties of sisal-leaf fibre-reinforced polyester composites prepared by resin transfer and compression moulding techniques. *Composites Science and Technology*, **67**, 453–461 (2007).
<https://doi.org/10.1016/j.compscitech.2006.08.025>
- [160] Kumar S., Kumar Y., Gangil B., Kumar Patel V.: Effects of agro-waste and bio-particulate fillers on mechanical and wear properties of sisal fibre based polymer composites. *Materials Today: Proceedings*, **4**, 10144–10147 (2017).
<https://doi.org/10.1016/j.matpr.2017.06.337>
- [161] Salisu A. A., Yakasai M. Y., Aujara K. M.: Physico-mechanical properties of chemically modified sisal fibre reinforced unsaturated polyester composites. *International Scholarly and Scientific Research and Innovation*, **10**, 81–88 (2016).
<https://doi.org/10.5281/zenodo.1338808>
- [162] Easwara Prasad G. L., Keerthi Gowda B. S., Velmurugan R.: Comparative study of impact strength characteristics of treated and untreated sisal polyester composites. *Procedia Engineering*, **173**, 778–785 (2017).
<https://doi.org/10.1016/j.proeng.2016.12.096>
- [163] Sangthong S., Pongprayoon T., Yanumet N.: Mechanical property improvement of unsaturated polyester composite reinforced with admicellar-treated sisal fibers. *Composites Part A: Applied Science and Manufacturing*, **40**, 687–694 (2009).
<https://doi.org/10.1016/j.compositesa.2008.12.004>
- [164] Sydenstricker T. H. D., Mochnaz S., Amico S. C.: Pull-out and other evaluations in sisal-reinforced polyester biocomposites. *Polymer Testing*, **22**, 375–380 (2003).
[https://doi.org/10.1016/S0142-9418\(02\)00116-2](https://doi.org/10.1016/S0142-9418(02)00116-2)

- [165] Joseph P. V., Mathew G., Joseph K., Groeninckx G., Thomas S.: Dynamic mechanical properties of short sisal fibre reinforced polypropylene composites. *Composites Part A: Applied Science and Manufacturing*, **34**, 275–290 (2003).
[https://doi.org/10.1016/s1359-835x\(02\)00020-9](https://doi.org/10.1016/s1359-835x(02)00020-9)
- [166] Sun Z., Wu M.: Effects of sol-gel modification on the interfacial and mechanical properties of sisal fiber reinforced polypropylene composites. *Industrial Crops and Products*, **137**, 89–97 (2019).
<https://doi.org/10.1016/j.indcrop.2019.05.021>
- [167] Joseph P. V., Rabello M. S., Mattoso L. H. C., Joseph K., Thomas S.: Environmental effects on the degradation behaviour of sisal fibre reinforced polypropylene composites. *Composites Science and Technology*, **62**, 1357–1372 (2002).
[https://doi.org/10.1016/s0266-3538\(02\)00080-5](https://doi.org/10.1016/s0266-3538(02)00080-5)
- [168] Chow C., Xing X., Li R.: Moisture absorption studies of sisal fibre reinforced polypropylene composites. *Composites Science and Technology*, **67**, 306–313 (2007).
<https://doi.org/10.1016/j.compscitech.2006.08.005>
- [169] Mukhopadhyay S., Srikanta R.: Effect of ageing of sisal fibres on properties of sisal – Polypropylene composites. *Polymer Degradation and Stability*, **93**, 2048–2051 (2008).
<https://doi.org/10.1016/j.polymdegradstab.2008.02.018>
- [170] Samouh Z., Molnar K., Boussu F., Cherkaoui O., El Moznine R.: Mechanical and thermal characterization of sisal fiber reinforced polylactic acid composites. *Polymers for Advanced Technologies*, **30**, 529–537 (2019).
<https://doi.org/10.1002/pat.4488>
- [171] Czigány T., Kovács J. G., Tábi T.: Basalt fiber reinforced poly (lactic acid) composites for engineering applications. in ‘19th International Conference on Composite Materials. Montreal, Canada’ 4377–4384 (2013).
- [172] Bax B., Müssig J.: Impact and tensile properties of PLA/Cordenka and PLA/flax composites. *Composites Science and Technology*, **68**, 1601–1607 (2008).
<https://doi.org/10.1016/j.compscitech.2008.01.004>
- [173] Chaitanya S., Singh I.: Processing of PLA/sisal fiber biocomposites using direct- and extrusion-injection molding. *Materials and Manufacturing Processes*, **32**, 468–474 (2016).
<https://doi.org/10.1080/10426914.2016.1198034>
- [174] Orue A., Jauregi A., Unsuain U., Labidi J., Eceiza A., Arbelaiz A.: The effect of alkaline and silane treatments on mechanical properties and breakage of sisal fibers and poly(lactic acid)/sisal fiber composites. *Composites Part A: Applied Science and Manufacturing*, **84**, 186–195 (2016).
<https://doi.org/10.1016/j.compositesa.2016.01.021>
- [175] Kittikorn T., Kongsuwan S., Malakul R.: Investigation of the durability of sisal fiber/PLA biocomposite through evaluation of biodegradability by means of microbial growth. *Journal of Metals, Materials and Minerals*, **27**, 23–34 (2017).
<https://doi.org/10.14456/jmmm.2017.xx>
- [176] Mishra S., Mohanty A. K., Drzal L. T., Misra M., Parija S., Nayak S. K., Tripathy S. S.: Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. *Composites Science and Technology*, **63**, 1377–1385 (2003).
[https://doi.org/10.1016/S0266-3538\(03\)00084-8](https://doi.org/10.1016/S0266-3538(03)00084-8)
- [177] Filho S. L. M. R., Oliveira P. R., Vieira L. M. G., Panzera T. H., Freire R. T. S., Scarpa F.: Hybrid biocomposites reinforced with sisal-glass fibres and Portland cement particles: A statistical approach. *Composites Part B: Engineering*, **149**, 58–65 (2018).
<https://doi.org/10.1016/j.compositesb.2018.05.019>
- [178] Akash, Sreenivasa Rao K. V., Venkatesha Gupta N. S., Arun kumar D. S.: Mechanical properties of sisal/coir fiber reinforced hybrid composites fabricated by cold pressing method. *IOP Conference Series: Materials Science and Engineering*, **149**, 012092/1–012092/7 (2016).
<https://doi.org/10.1088/1757-899X/149/1/012092>
- [179] Akash, Venkatesha Gupta N. S., Sreenivas Rao K. V.: An experimental study on sisal/hemp fiber reinforced hybrid composites. *Materials Today: Proceedings B*, 7383–7387 (2018).
<https://doi.org/10.1016/j.matpr.2017.11.408>
- [180] Aslan M., Tufan M., Küçükömeroğlu T.: Tribological and mechanical performance of sisal-filled waste carbon and glass fibre hybrid composites. *Composites Part B: Engineering*, **140**, 241–249 (2018).
<https://doi.org/10.1016/j.compositesb.2017.12.039>
- [181] Xie Q., Li F., Li J., Wang L., Li Y., Zhang C., Xu J., Chen S.: A new biodegradable sisal fiber–starch packing composite with nest structure. *Carbohydrate Polymers*, **189**, 56–64 (2018).
<https://doi.org/10.1016/j.carbpol.2018.01.063>
- [182] de Oliveira F., da Silva C. G., Ramos L. A., Frollini E.: Phenolic and lignosulfonate-based matrices reinforced with untreated and lignosulfonate-treated sisal fibers. *Industrial Crops and Products*, **96**, 30–41 (2017).
<https://doi.org/10.1016/j.indcrop.2016.11.027>
- [183] Kılınc A. C., Durmuşkahya D., Seydibeyoğlu M. O.: Natural fibers. in ‘Fiber technology for fiber-reinforced composites’ (eds.: Seydibeyoğlu M. O., Mohanty A., Misra M.) Elsevier, Amsterdam, 209–235 (2017).
<https://doi.org/10.1016/B978-0-08-101871-2.00010-2>
- [184] Mishra M.: *Encyclopedia of polymer applications*. Taylor and Francis, London (2019).
- [185] Armecin R. B., Sinon F. G., Moreno L. O.: Abaca fiber: A renewable bio-resource for industrial uses and other applications. in ‘Biomass and bioenergy’ (eds.: Hakeem K., Jawaid M., Rashid U.) Springer, Cham, 107–118 (2014).
https://doi.org/10.1007/978-3-319-07578-5_6

- [186] Bledzki A. K., Franciszczak P., Osman Z., Elbadawi M.: Polypropylene biocomposites reinforced with softwood, abaca, jute, and kenaf fibers. *Industrial Crops and Products*, **70**, 91–99 (2015).
<https://doi.org/10.1016/j.indcrop.2015.03.013>
- [187] Saragih S. W., Lubis R., Wirjosentono B., Eddyanto.: Characteristic of abaca (*Musa textilis*) fiber from Aceh Timur as bioplastic. *AIP Conference Proceedings*, **2049**, 020058/1–020058/7 (2018).
<https://doi.org/10.1063/1.5082463>
- [188] Baltazar-y-Jimenez A., Bismarck A.: Wetting behaviour, moisture up-take and electrokinetic properties of lignocellulosic fibres. *Cellulose*, **14**, 115–127 (2006).
<https://doi.org/10.1007/s10570-006-9092-x>
- [189] Bar M., Alagirusamy R., Das A.: Flame retardant polymer composites. *Fibers and Polymers*, **16**, 705–717 (2015).
<https://doi.org/10.1007/s12221-015-0705-6>
- [190] Rohit K., Dixit S.: A review - Future aspect of natural fiber reinforced composite. *Polymers from Renewable Resources*, **7**, 43–59 (2018).
<https://doi.org/10.1177/204124791600700202>
- [191] Vijayalakshmi K., Neeraja Y. K., Kavitha A., Hayavadana J.: Abaca fibre. *Transactions on Engineering and Sciences*, **2**, 2347–1875 (2014).
- [192] Punyamurthy R., Sampathkumar D., Srinivasa C. V., Bennehalli B.: Effect of alkali treatment on water absorption of single cellulosic abaca fiber. *Bioresources*, **7**, 3515–3524 (2012).
<https://doi.org/10.15376/biores.7.3.3515-3524>
- [193] Delicano J. A.: A review on abaca fiber reinforced composites. *Composite Interfaces*, **25**, 1039–1066 (2018).
<https://doi.org/10.1080/09276440.2018.1464856>
- [194] Teramoto N., Urata K., Ozawa K., Shibata M.: Biodegradation of aliphatic polyester composites reinforced by abaca fiber. *Polymer Degradation and Stability*, **86**, 401–409 (2004).
<https://doi.org/10.1016/j.polyimdegradstab.2004.04.026>
- [195] Shibata M., Ozawa K., Teramoto N., Yosomiya R., Takeishi H.: Biocomposites made from short abaca fiber and biodegradable polyesters. *Macromolecular Materials and Engineering*, **288**, 35–43 (2003).
<https://doi.org/10.1002/mame.200290031>
- [196] Shibata M., Takachiyo K-I., Ozawa K., Yosomiya R., Takeishi H.: Biodegradable polyester composites reinforced with short abaca fiber. *Journal of Applied Polymer Science*, **85**, 129–138 (2002).
<https://doi.org/10.1002/app.10665>
- [197] Bledzki A. K., Mamun A. A., Faruk O.: Abaca fibre reinforced PP composites and comparison with jute and flax fibre PP composites. *Express Polymer Letters*, **1**, 755–762 (2007).
<https://doi.org/10.3144/expresspolymlett.2007.104>
- [198] Haque M., Rahman R., Islam N., Huque M., Hasan M.: Mechanical properties of polypropylene composites reinforced with chemically treated coir and abaca fiber. *Journal of Reinforced Plastics and Composites*, **29**, 2253–2261 (2009).
<https://doi.org/10.1177/0731684409343324>
- [199] Vilaseca F., Valadez-Gonzalez A., Herrera-Franco P. J., Pèlach M. À., López J. P., Mutjé P.: Biocomposites from abaca strands and polypropylene. Part I: Evaluation of the tensile properties. *Bioresource Technology*, **101**, 387–395 (2010).
<https://doi.org/10.1016/j.biortech.2009.07.066>
- [200] Liu K., Zhang X., Takagi H., Yang Z., Wang D.: Effect of chemical treatments on transverse thermal conductivity of unidirectional abaca fiber/epoxy composite. *Composites Part A: Applied Science and Manufacturing*, **66**, 227–236 (2014).
<https://doi.org/10.1016/j.compositesa.2014.07.018>
- [201] Liu L., Cheng L., Huang L., Yu J.: Enzymatic treatment of mechanochemical modified natural bamboo fibers. *Fibers and Polymers*, **13**, 600–605 (2012).
<https://doi.org/10.1007/s12221-012-0600-3>
- [202] Bledzki A. K., Mamun A. A., Jaszkievicz A., Erdmann K.: Polypropylene composites with enzyme modified abaca fibre. *Composites Science and Technology*, **70**, 854–860 (2010).
<https://doi.org/10.1016/j.compscitech.2010.02.003>
- [203] Venkatasubramanian H., Chaithanyan C., Raghuraman S., Panneerselvam T.: Evaluation of mechanical properties of abaca glass banana fiber reinforced hybrid composite. *International Journal of Innovative Research in Science, Engineering and Technology*, **3**, 8169–8177 (2014).
- [204] Vijaya Ramnath B., Manickavasagam V. M., Elanchezhian C., Vinodh Krishna C., Karthik S., Saravanan K.: Determination of mechanical properties of intra-layer abaca–jute–glass fiber reinforced composite. *Materials and Design*, **60**, 643–652 (2014).
<https://doi.org/10.1016/j.matdes.2014.03.061>
- [205] Paglicawan M. A., Basilia B. A., Kim B. S.: Water uptake and tensile properties of plasma treated abaca fiber reinforced epoxy composite. *Composites Research*, **26**, 165–169 (2013).
<https://doi.org/10.7234/composres.2013.26.3.165>
- [206] Malenab R. A. J., Ngo J. P. S., Promentilla M. A. B.: Chemical treatment of waste abaca for natural fiber-reinforced geopolymer composite. *Materials*, **10**, 579/1–579/19 (2017).
<https://doi.org/10.3390/ma10060579>