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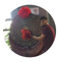

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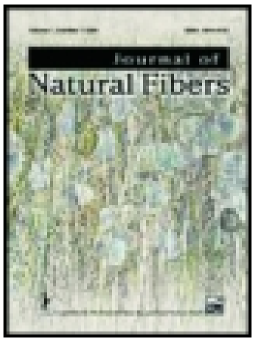

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Bast Fiber Reinforced Green Polymer Composites: A Review on Their Classification, Properties, and Applications

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ABSTRACT

Due to the increased public awareness in ensuring a sustainable and long-lasting world, both academic and industrial researchers are trying to use eco-friendly and biodegradable materials in every sphere of life. Petroleum-based synthetic materials are nonrenewable, hazardous, and costly. In contrast, natural fibers are mainly derived from plant-based sources, which are recyclable, renewable, sustainable, abundantly available, and cheap. Hence, the use of natural fibers in the fabrication of composite materials is increasing dramatically. These are used as a reinforcement with the polymer matrix to fabricate the composites. Although a massive amount of research works has been performed to develop green composites, until now the composite fabrication process is facing some terrific problems such as the lower adhesion tendency of the composites, due to the presence of the hydrophilic natural fibers and hydrophobic polymer matrix. Researchers are trying to find out the optimum combination of the composites that can be able to exhibit excellent mechanical properties for the application areas where greater strength is a must. This review is focusing on the composite materials fabricated from the bast fibers, a branch of the natural fibers, with various thermoplastic and thermosetting polymers, and their potential application areas.

抽象

Bombyx mori丝织物一般在高温下用酸性染料染色, 具有能耗过高的缺点. 在目前的工作中, 使用芳香胺的重氮盐对丝织物进行原位着色, 力求以更少的能耗实现高色牢度. 随后, 利用过硫酸铵（APS）的引发剂对三甲基氯化铵（DMC）进行嫁接共聚，进一步增强丝绸的抗菌能力。 液相色谱-质谱法（LC-MS）、FTIR和拉曼光谱的结果验证了安卓盐和酪氨酸模型化合物的偶氮染料的形成. 丝织品原位着色后, 色深高, 色牢度好。对于与4-乙烯基苯胺（DVA）的二氮盐结合的织物, 引入的乙烯基组可能会进一步与DMC进行嫁接共聚, 从而产生明显的抗菌效果, 抗菌率为96.38%. 同时, 联合治疗后未发现加强损失. 原位着色和APS启动的级联抗菌功能化相结合, 为丝绸织物在温和处理条件下的染色和功能化提供了一种新颖节能的方法.

KEYWORDS
Natural bast fibers; thermoplastic and thermosetting polymers; classification; biodegradability; eco-friendly and sustainable composites; properties and applications

Introduction

Composites are generally known as materials having multifunctional physical and chemical properties, which are manufactured by using two or more individual materials of different characteristics (Mastura et al. 2017; Sahu and Gupta 2017). Composites are made of two main individual substances

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such as matrix (e.g., metals, ceramics, or polymers) and reinforcing agents (e.g., particles, flakes, or fibers), where the matrix bounded the reinforcing agents to ensure not only the appropriate bonding but also the greater mechanical properties than that of the discrete materials (Mastura et al. 2017; Faruque et al. 2019). A woven fabric named “Fiberglass,” which is manufactured with plastic (acted as a matrix) and glass fiber (acted as a reinforcement) is believed to be the very first fiber-reinforced polymer composites of the modern world and widely used in boat hulls, sports, panels, and automobiles (Dudarev, Volegov, and Kurzanov 2017; Mrazova 2013). Textiles, in the form of fiber, yarn and fabric are being used from prehistoric time and currently, it is considered as one of the most polluting industries all over the world (Cai et al. 2019; Al Faruque, Remadevi, Razal, and Naebe 2020b; Al Faruque, Remadevi and Razal 2020a; Wang et al. 2020; Sarkar, Al Faruque, and Mondal 2021). Although textile fibers were predominantly used in the clothing and fashion industry, currently these are used in advanced manufacturing areas such as medical, agriculture, automotive, military, building construction, and sports (Akter, Azim, and Al Faruque 2014; Alam et al. 2018; Cai et al. 2021; Kiruthika 2017; Chowdhury, Nasrin, and Al Faruque 2017; Sadrmanesh and Chen 2019). The use of natural fibers is increasing significantly compared to the synthetic fibers for the fabrication of materials to utilize in such application areas due to their outstanding eco-friendly, compatible, and biodegradable properties (Syduzzaman et al. 2020; Dong 2018; Lau et al. 2018; Faruque et al. 2021; Md, Jonayet, and Al Faruque 2017). However, synthetic fibers are derived from petroleum-based nonrenewable sources and neither biodegradable nor biocompatible (Cai et al. 2021). Besides, the separation of the synthetic materials from the products after their lifetime is troublesome and almost impossible (Aisyah et al. 2021; Franco 2017; Peças et al. 2018). Hence, to ensure a “green and sustainable” environment, the fabrication of natural fiber-based polymer composites is a crying need to replace the use of synthetic fibers (Ciccarelli et al. 2020; Pickering, Efendy, and Le 2016; Ramamoorthy, Skrifvars, and Persson 2015; Subramani et al. 2017). Because the natural fibers have shown several excellent properties rather than the synthetic fibers such as low density, cheap, biodegradability, renewability, and biocompatibility (Ciccarelli et al. 2020; Pickering, Aruan Efendy, and Le 2016; Subramani et al.

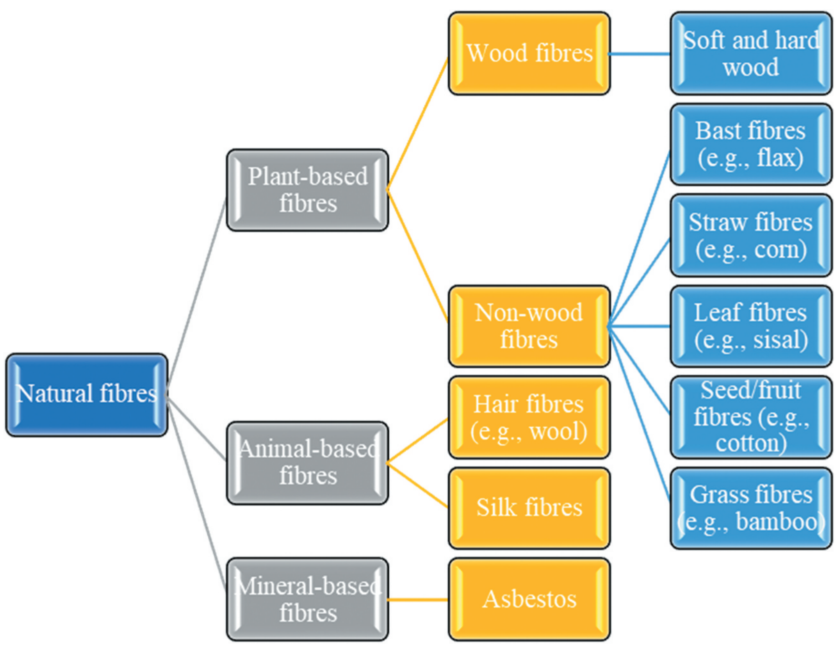

Figure 1. Classification of the natural fibers (Pico and Steinmann 2016; Ciccarelli et al. 2020; Mohammed et al. 2015; Pickering, Aruan Efendy, and Le 2016, 2016; Ramamoorthy, Skrifvars, and Persson 2015; Subramani et al. 2017).

2017). Therefore, the use of natural fibers in the fabrication of composites for high-tech applications is certainly an alternative way to reduce the use of synthetic-based materials.

Natural fibers are mainly classified into three categories such as plant-based fibers, animal-based fibers, and mineral-based fibers (Ciccarelli et al. 2020; Subramani et al. 2017). The plant-based fibers are mainly classified into two categories such as wood fibers (e.g., softwood and hardwood) and non-wood fibers (e.g., cotton, jute, and sisal) depending on their origin (Mohammed et al. 2015; Pickering, Aruan Efendy, and Le 2016; Ramamoorthy, Skrifvars, and Persson 2015; Subramani et al. 2017). On the other hand, the non-wood fibers are categorized into five classes such as bast fibers (jute, flax, and hemp), straw fibers (corn, wheat, and rice), leaf fibers (sisal, banana, and pineapple), seed/fruit fibers (coir and cotton), and grass fibers (bamboo and elephant grass) (Dixit et al. 2017; Pennells et al. 2020; Syduzzaman et al. 2020). The animal-based fibers are mostly obtained from hair sources (e.g., sheep, alpaca, and cashmere) and silk fibers (Mitra 2014; Al Faruque, Remadevi, Razal; Wang et al. 2020a). The mineral-based fibers are sourced from different mineral sources like asbestos (Pickering, Aruan Efendy, and Le 2016). A detailed classification of the natural fibers is shown in Figure 1 (Ciccarelli et al. 2020; Mohammed et al. 2015; Pickering, Aruan Efendy, and Le 2016; Ramamoorthy, Skrifvars, and Persson 2015; Subramani et al. 2017). Although all of these natural fibers are used as the reinforcing agents while fabricating the bio-based composites materials, the use of plant-based natural fibers is higher compared to the animal and mineral-based fibers, as animal-based fibers are costly than plant-based fibers and asbestos is carcinogenic and possessed other health issues (Pickering, Aruan Efendy, and Le 2016; Väisänen, Das, and Tomppo 2017). However, the use of basalt fiber, which is originated from natural mineral sources, is currently applying in a significant way while preparing the composites used for textile and non-textile-based applications (Asadi et al. 2017; Pham 2020; Ruffen and Mahltig 2021). The plant-based natural fibers are used as the reinforcing agents in fabricating the composites to improve the dimensional stability, stiffness, tensile strength, breaking strength, toughness, and modulus of the composite materials because of their outstanding physicomechanical and environmentally friendly properties (Syduzzaman et al. 2020). Therefore, it is high time to utilize the bast fiber reinforced polymer composites to ensure a safe and sound environment. This review is aiming to demonstrate a thorough review of the required properties of the bast fibers and the polymer matrices

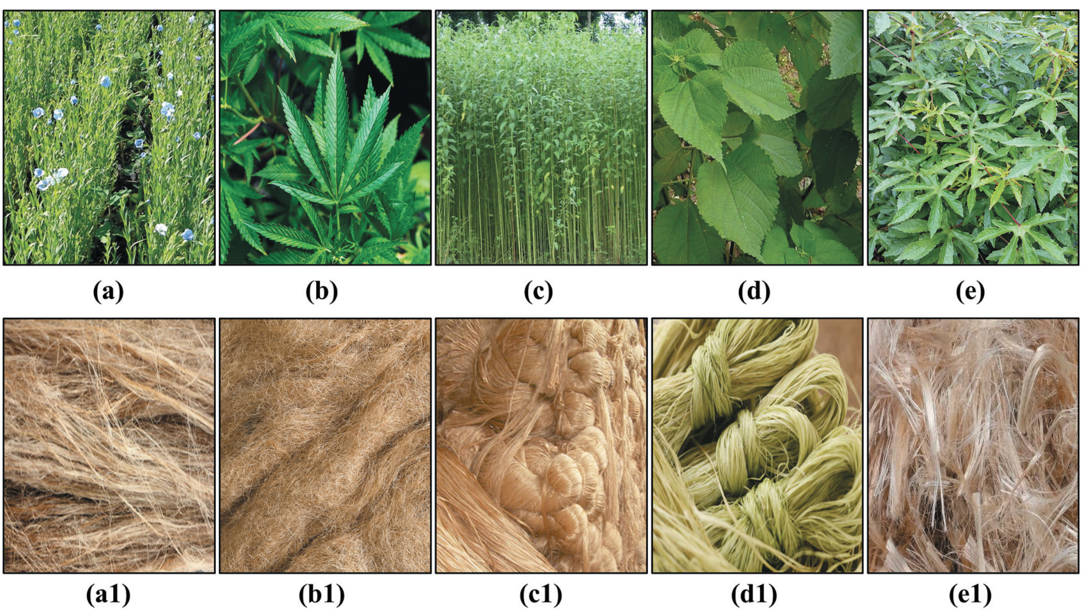

Figure 2. Digital images of different bast fibers: (a-a1) flax fibers, (b-b1) hemp fibers, (c-c1) jute fibers, (d-d1) ramie fibers, and (e-e1) kenaf fibers.

Table 1. Worldwide production of the bast fibers per annum (La Mantia and Morreale 2011; John and Thomas 2008; Yan, Chouw, and Jayaraman 2014; Shahzad 2012; Du, Yan, and Kortschot 2015).

Fibers	Worldwide production (KT)
Flax	830
Hemp	214
Jute	2300–2800
Ramie	100–130
Kenaf	970

Table 2. Chemical constituent of the bast fiber along with their moisture content (Mohammed et al. 2015; Pickering, Aruan Efendy, and Le 2016; Ramamoorthy, Skrifvars, and Persson 2015).

Fibers	Cellulose (wt.%)	Hemicellulose (wt.%)	Lignin (wt.%)	Pectin (wt.%)	Wax (wt.%)	Moisture content (wt.%)
Flax	71	18.6–20.6	2.2	2.3	1.7	7–10
Hemp	70.4–74.4	17.9–22.4	3.7–5.7	0.9	0.8	8–11
Jute	61–71.5	13.6–20.4	12–13	0.2	0.5	10–14
Ramie	68.6–76.2	13.1–16.7	0.6–0.7	1.9	0.3	7–15
Kenaf	35–57	21.5	15–19	3–5	-	6–12

Table 3. Mechanical properties of the bast fibers (Mohammed et al. 2015; Ramamoorthy, Skrifvars, and Persson 2015; Pickering, Aruan Efendy, and Le 2016; Maghsoudi-Ganjeh et al. 2019; Davoodi et al. 2011).

Fibers	Diameter (μm)	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Flax	40–600	1.5	88–1500	27.6	2.7–3.2
Hemp	25–500	1.47	550–900	70	1.6
Jute	25–200	1.3–1.49	393–800	13–26.5	1.16–1.8
Ramie	35–60	1.55	400–938	61.4–128	1.2–3.8
Kenaf	30–50	1.2	295–930	53	1.6–6.9

to fabricate the bast fiber reinforced polymer composites using various bast fibers such as flax, hemp, jute, ramie, and kenaf fibers. In addition, the composite fabrication process and end-uses of the bast fiber reinforced polymer composites were also reviewed and discussed in this review manuscript to provide extensive knowledge to the readers and assist in further investigation and research on this topic.

Physical, chemical, and mechanical properties of the bast fibers

Bast fibers are plant-based cellulosic fibers and are obtained primarily from the bark of the plants. The cell wall of the bast fibers is composed of bundles of cellulosic chains, without any cotton-like twist along their lengthwise direction. Flax (*Linum usitatissimum*), hemp (*Cannabis sativa*), jute (*Corchorus capsularis/Corchorus olitorius*), ramie (*Boehmeria nivea*), and kenaf (*Hibiscus cannabinus*) are the main example of the widely used bast fibers for the fabrication of the fiber-reinforced polymer composites (FRPC) (Mohammed et al. 2015; Ramamoorthy, Skrifvars, and Persson 2015). Figure 2 represents the digital images of the plants and the extracted fibers. Table 1 summarizes the yearly production of bast fiber all over the world.

Cellulose is the main chemical constituent of the bast fibers. Apart from this, other components such as hemicellulose, lignin, pectin, and wax are also present in the chemical structure of the bast fibers (Table 2) (Mohammed et al. 2015; Ramamoorthy, Skrifvars, and Persson 2015). Due to the presence of cellulose, hemicellulose, and lignin, the moisture and mechanical properties of the bast fibers are higher than that of the synthetic fibers (Kumar et al. 2017; Kumar, Prasad, and Patel 2017; Yan, Chouw, and Jayaraman 2014). It has been found that the existence of higher cellulosic content

Table 4. Properties of the polymers (Yan, Chouw, and Jayaraman 2014; Yun et al. 2016; Zini and Scandola 2011; Ke et al. 2010; Stapulionienė et al. 2016; Kucinska-Lipka, Gubanska, and Sienkiewicz 2017).

Polymer	Density (g/cm^3)	Glass Temperature (^0C)	Melting Temperature (^0C)	Thermal Conductivity (W/m. ^0K)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation (%)
Polyethylene (PE)	0.93	−78	105–115	0.33–0.51	15	0.8	90–800
Polypropylene (PP)	0.92	−20	130	0.1–0.2	40	1.9	15–700
Polystyrene (PS)	1.1	100	240	0.03	40	3	1–2.5
Polycarbonates (PC)	1.2	147	157	0.19	70	2.6	80–150
Polyvinyl Acetate (PVA)	1.19	30–45	200	0.31	40	1.7	1.76
Polyvinyl chloride (PVC)	1.4	82	160	0.19	51	2.4	50–80
Polylactic acid (PLA)	1.2–1.4	60–65	150–160	1.13	50	3.5	6.5
Polyglycolic acid (PGA)	1.53	35–40	225–230	0.35	70	0.3	5.5–6.5
Polyurethane (PU)	0.8–1.4	−63	240	0.022	10–30	0.2–0.3	100–380
Epoxy	1.1–1.4	50–80	177	0.14	35–100	3–6	1–6
Starch	1.5	20–60	0	0.38	5–9	0.2–0.3	35–100

eventually enhances the strength of the fibers (Kumar, Prasad, and Patel 2017; Ramamoorthy, Skrifvars, and Persson 2015). Therefore, in some cases, the bast fibers showed higher mechanical strength than that of the other plant-based natural fibers and were highly used in the production of the fiber-based reinforced polymer composites (FRPC) (Pickering, Aruan Efendy, and Le 2016; Ramamoorthy, Skrifvars, and Persson 2015). The diameter, density, and other mechanical properties of the bast fibers are presented in Table 3.

Polymer matrix properties

The fiber-reinforced polymer composites (FRPC) are formed with a reinforcing agent (fibers) and matrix (polymer). By the means of adhesion, the polymeric matrix binds the fibers together to ensure the proper contour and strength of the composites. The polymers can be obtained from thermoplastics, thermoset, or even biopolymers sources. Thermoplastic polymers (e.g., polypropylene, polycarbonate, polyimides, polyethylene terephthalate) are weakly attached with the van der Waals forces and extensively used in producing composites by exhibiting excellent toughness and resistance to wear and tear (Begum, Fawzia, and Hashmi 2020; Gouzman et al. 2019; Yun et al. 2016). In contrast, the thermoset polymers (e.g., epoxy, silicone, polyurethane) are formed into a 3D linkage arrangement by the sturdy covalent bonds and cross-links, which make them tough (Gouzman et al. 2019; Mohd Nurazzi et al. 2017). The commercial production and utilization of the green composites are still at a laboratory-based research level with some unwanted drawbacks due to some inherent properties of the natural fibers such as higher water absorbing tendency (Moustafa et al. 2019; Teuber et al. 2016; Zini and Scandola 2011). Hence, this review intended to focus on the FRPC fabricated with the thermoplastic and thermoset polymers with their extensive application areas. The physical and mechanical properties of the polymers are tabulated in Table 4.

Bast fiber reinforced thermoplastic and thermoset polymer composites

Due to the increasing awareness toward the environment, global warming, and tendency of creating a safe, sound, and liveable atmosphere for the next generation, the government agencies, industry, and research personnel are focusing on the production and use of eco-friendly and sustainable items in their daily life.

Flax Fiber Reinforced Thermoplastic and Thermoset Polymer composites

Flax fibers are composed of 70% cellulose and due to this criterion, it was highly used with various thermoplastic polymers to fabricate the bio-based composites for diversified applications. Bar et al. fabricate flax/polypropylene composites using the traditional film stacking method, compression molding method, hybrid yarn spinning method, friction spinning technique, and thermally bonding method and studied the mechanical properties of the composites (Bar, Alagirusamy, and Das 2018, 2019). Polyethylene, another example of thermoplastic polymer, is widely used to fabricate bio-based composites with flax fibers. Recently, the flax fibers (FF) and wood flour (WF) were used as a reinforcement and added with the high-density polyethylene (HDPE) to produce the bio-composites using the extrusion method (Zhang et al. 2018). The results of this study verified that the mechanical properties of the composites increase with the addition of a higher proportion of flax fibers into the composites, which supports the findings of the previous researchers (Zhang et al. 2018). These composites with greater mechanical properties can be used in producing automotive and building construction materials. The phenolic molecules of lignin, which is an important part of flax fiber, possessed antioxidant properties that enhance the stability of the polyolefin (Van Schoors, Gueguen Minerbe, et al. 2018; Van Schoors, Minerbe, et al. 2018; Yang, Ching, and Chuah 2019). Besides, apart from enhancing the mechanical properties of the flax/polyethylene composites, it has been found that the presence of lignin in the flax fibers restrain the thermo-oxidative aging of the flax/polyethylene composites by improving the Oxidative Induction Time of the matrices from 0 to 25 minutes (Van Schoors et al. 2018). This is a tremendous achievement of the natural flax fibers that further limit the use of synthetic-based antioxidants with the polyethylene matrix and prevent the deterioration of the environment. Flax fibers are widely used as a reinforcing agent while preparing the fiber-reinforced thermoset polymer composites owing to their availability, cost-effectiveness, yield, and outstanding mechanical properties (Chilali et al. 2018; Syduzzaman et al. 2020). Besides, very often the fabricated composite structures demonstrated excellent physicomechanical properties that were comparable to the glass-fiber-reinforced composite materials, which is an additional benefit from the renewability and environmental friendliness of the composites viewpoint (Pantaloni et al. 2021; Peças et al. 2018). Fiore et al. investigated the impact of environmentally friendly surface treatment of flax fiber by applying sodium bicarbonate (Na_2CO_3) on the flax fiber-reinforced thermoset composites, which was produced via vacuum-assisted resin infusion process and using low viscosity epoxy resin as a polymer matrix (Fiore, Scalici, and Valenza 2018). An improvement of almost 20% and 45% in the tensile strength and tensile modulus was observed for the 10 wt.% of Na_2CO_3 treated samples compared to the untreated ones. Flexural strength and modulus were also improved to nearly 177 MPa and 13 GPa with an insignificant amount of changes in their transition temperature, which might be due to the excellent fiber-matrix adhesion that was further confirmed by the observation of fracture surfaces through SEM (Fiore, Scalici, and Valenza 2018). Recently, Xu et al. used a solution of methacrylate lignosulfonate as a possible compatibilizer to fabricate the flax fiber/polyester composites (Xu et al. 2020). The results indicated that both the tensile and flexural properties of the composite materials enhanced due to the treatment of the compatibilizer which could be due to the outstanding fiber-matrix bonding without pulling out the fibers from the composite structures that can easily be seen from the morphological study of the composites (Xu et al. 2020).

Hemp fiber reinforced thermoplastic and thermoset polymer composites

Hemp fiber is another branch of bast fibers that are extremely used in the development of bio-based composites to prevail over the use of synthetic-based composite materials in the diversified application areas (Aisyah et al. 2021; Dixit et al. 2017). Although natural fibers possessed greater merits over synthetic fibers, the mass production of the composites is often difficult, for example, weak binding or adhesion of the natural reinforcement and the polymer matrix materials, owing to their hydrophilic and hydrophobic nature (Sullins et al. 2017; Syduzzaman et al. 2020). To overcome this strain and increasing the bonding between the reinforcement and polymer matrix, the hemp fiber (reinforcing agent) was treated with the sodium hydroxide (NaOH), and the polymer matrix was treated with the maleic anhydride grafted polypropylene (MAPP) to fabricate the hemp/polypropylene composites (Etaati et al. 2014; Sullins et al. 2017). The results have shown that due to the chemical treatment the bonding and the mechanical properties of the composites were enhanced. Moreover, the authors concluded that the composites produced with the higher proportion of hemp fiber possessed higher mechanical properties that could be used in the automobile industry (Roumeli et al. 2015; Sullins et al. 2017). Hemp fibers are stronger and that's why we highly considered them as a reinforcement while fabricating composites (Nayak et al. 2020; Syduzzaman et al. 2020). Besides, having an outstanding strength-to-weight ratio of hemp fiber makes it a desirable composite reinforcement from the technical, ecological, and economical points of view. Swapan et al. investigated the mechanical properties of hemp reinforced unsaturated polyester (UP) by varying the fiber content and applying pre-treatments to the hemp fibers (Sawpan, Pickering, and Fernyhough 2013). The effect of alkali treatment on the mechanical properties of the hemp/polyester composites that were fabricated by the hand lay-up technique was investigated by keeping the amount of hemp fiber constant (25 wt.%) in the composite material, which was used as a control without any alkali treatment (Gupta and Gond 2017). Thereafter, for the alkali treatment, the authors kept the concentration of NaOH at 5, 10, 15%. After thorough investigation, the authors concluded that the hemp/polyester composite material which was treated with 5% NaOH concentration showed better mechanical properties, 26% improved tensile strength and 16% increased modulus than that of the untreated control hemp/polyester composite material, which was due to the increased surface roughness for the alkali treatment that resulted in the better mechanical interlocking of the reinforcement and the matrix (Gupta and Gond 2017). Recently, Neves et al. conducted a comparative study between thermoset matrices (epoxy and polyester) reinforced with hemp fiber at 10%, 20%, and 30% (v/v) inside the steel molds (Neves et al. 2020). The hemp/epoxy composites produced with 30% hemp fibers demonstrated higher flexural and tensile strength compared to the hemp/polyester composites manufactured with the same proportion of hemp fiber content (30%). The morphological study of the hemp/polyester composites revealed the presence of internal cracks, which might cause lower internal bonding between the hemp fiber and polyester and resulted in reduced mechanical properties than that of the hemp/epoxy composites. The authors concluded that the hemp/epoxy composites can be used in preparing a multifaceted armor system for ballistic protection (Neves et al. 2020).

Jute fiber reinforced thermoplastic and thermoset polymer composites

Jute fiber is another example of bast fibers that grows extensively in the Indian subcontinent, for example, India, Pakistan, Bangladesh, Sri Lanka, Bhutan, Nepal, and the Maldives, because of the climatic conditions present in this region (Gunti, Ratna Prasad, and Gupta 2018; Meshram and Palit 2013; Srivastava and Rastogi 2020). Both academic and industry researchers are using both virgin and waste jute fibers to fabricate the reinforced composites because of their ample availability in nature and eco-friendliness. Recently, a single screw extrusion molding technique was used to prepare the short jute fibers (20%) reinforced polypropylene composites (80%) and treated with different nonhalogenated fire retardants to evaluate the flame resistance property of the composites. In similar, the addition of jute fibers with polyethylene also enhanced the mechanical properties of the composite materials compared to the control polyethylene laminates and these could be commercially used in industrial, building, and automobile applications (Ovalı and Sancak 2020). One of the main reasons for these increased mechanical properties of the composite structure might be the absence of any porous and voids into the composites, excellent adhesion between the reinforcing agent and the matrix (Sayem, Haider, and Sayeed 2020). Biodegradable and eco-friendly jute fiber reinforced polymer composites can be utilized in different application areas than synthetic composites to ensure environmental sustainability. A study has been conducted by Gopinath et al. on evaluating the mechanical properties of jute fiber reinforced epoxy and polyester composites where the fiber length was 5–6 mm, treated with 5% & 10% NaOH, and the fiber-matrices weight percentage ratio was kept 18:82 (Gopinath, Kumar, and Elayaperumal 2014). It has been found that the tensile strength and modulus of jute/epoxy composites are higher rather than the jute/polyester composite, which might be due to the lack of stronger adhesion between the reinforcement and matrix in the case of jute/polyester composites than that of jute/epoxy composites that were previously seen in the literature (Gopinath, Senthil Kumar, and Elayaperumal 2014; Neves et al. 2020). Recently, another investigation has been accomplished to better understand the phenomenon of varying mechanical properties of jute/epoxy and jute/polyester composites where the composite materials were fabricated using the hand lay-up technique (Kaushik, Jaivir, and Mittal 2017). The mechanical properties of the composite materials have been evaluated at different fiber loadings. The results demonstrated that the jute/epoxy composites possessed higher mechanical properties compared to the jute/polyester composites, and the authors concluded that due to the poor interfacial bonding between jute and polyester it showed lower mechanical properties than jute/epoxy composites (Kaushik, Jaivir, and Mittal 2017).

Ramie fiber reinforced thermoplastic and thermoset polymer composites

Ramie is the toughest bast fiber that yielded its fiber from the bark of the canes, which supplies exceptional raw material for blending with natural and synthetic fibers with higher luster, tenacity, brightness, and resistance to light, heat, alkali, and acid (Kiruthika 2017; Rehman et al. 2019). The authors concluded that the composites fabricated with a higher proportion of ramie (30%) possessed lower thermal degradation temperature, higher crystallization rate, and greater impact strength. The impact of die structure on the morphological, thermal, and mechanical properties of the ramie/polypropylene composites prepared by solid-state extrusion technique has been explored by Wang et al. (Wang et al. 2020). The results showed that the microfibrils inside the composites can be oriented in an excellent order toward the direction of the extrusion, which helps in enhancing not only the crystallinity index but also the tensile and flexural strength of the composites and generate the possibility of their extensive applications in the automobile, building construction, and packaging industries (Sapiai et al. 2020; Wang et al. 2020). Comparable specific modulus and strength to the traditional synthetic fibers have made ramie fiber an excellent alternative to fabricating the fiber-reinforced composite materials. Simonassi et al. investigated the mechanical properties improvement of the polyester (PET) via aligned ramie fiber reinforcement (Simonassi et al. 2017). Using the mold pressing technique, the authors were able to fabricate the composite with 30% ramie fiber reinforcement. The results revealed that with the incorporation of 30% fiber content, the flexural strength, impact strength, and tensile strength of the ramie/PE composites increased more than 2–3 times (Simonassi et al. 2017). In another study, ramie fiber was coupled with unsaturated polyester (UP) and phosphorous/nitrogen-containing silane coupling agent using the hand lay-up/oven vacuum bag technique to investigate the mechanical and fire safety properties of the composite materials (Chu et al. 2018). The results showed that the flame retardancy of the composite material dramatically enhanced by adding only 10% of ammonium polyphosphate, and the tensile strength was also tremendously increased (Chu et al. 2018). In another study, Djafar et al. studied the effects on tensile and bending strength by varying the ramie fibers weight and the number of layer (plies) of woven ramie fabric of ramie/epoxy composites (Djafar, Renreng, and Jannah 2020). A 6–8 hrs compression molding method was used to fabricate the composite and it has been found that the moisture content of such composites decreased with the increased proportion of woven ramie layers and the fiber weight, and the tensile and bending strength of the composite increased with the number of layers and amount of fiber content (Djafar, Renreng, and Jannah 2020). Recently, a multi-layered armor system (MAS) has been developed using ramie/epoxy composites to protect from the bullets of 7.62 mm, where the ramie content was 30 wt.% (Braga et al. 2018). The results demonstrated that the ramie/epoxy composites have as much ballistic protection capability as the MAS prepared with epoxy/aramid composites and with Kevlar® (Braga et al. 2018). Moreover, the ramie/epoxy composites are eco-friendly and nearly 14% cheaper compared to the other ballistic protection materials (Braga et al. 2018).

Kenaf fiber reinforced thermoplastic and thermoset polymer composites

Kenaf fibers can widely be used in the fabrication of composite materials due to their higher mechanical properties. Recently, zinc oxide (ZnO) nanoparticles have been incorporated into the kenaf/polyester composites and their several properties such as thermal, mechanical, water uptake and biodegradation have been studied (Mohammed et al. 2019). The results showed that due to the presence of ZnO nanoparticles both the thermal stability and the mechanical properties of the kenaf/ZnO/polyester composites improved immensely rather than the neat kenaf/polyester composites. Besides, the composite structure with the highest proportion of kenaf showed greater water uptake tendency and superior biodegradability (Mohammed et al. 2019). Therefore, this composite can be used in a dry environment (for example, in indoor applications)and at the same time, the products would be highly eco-friendly as of their biodegradability. On the other hand, to accelerate the recyclability of the composite materials and ensuring the sustainability of the environment, grounded waste polypropylene was used as a recycled polymer matrix with the kenaf fiber snippets to fabricate the fiber-reinforced polymer composite (Kim and Cho 2020). The composite materials exhibited higher flexural properties (98%) and impact strength (55%) compared to the composites fabricated with the virgin polypropylene polymer matrix (Kim and Cho 2020). These results are recommending that the use of waste polypropylene polymer matrix would not only be a cheap, feasible, and eco-friendly approach to prepare the composites, but it would also be a method of fabricating and using biodegradable and sustainable commodities for diversified applications. Kenaf fiber, due to having low density, commercial sustainability, no health risk, higher specific strength, and modulus, and renewability makes it an important reinforcement in the composite industry (Mahmud et al. 2021; Ramesh 2016; Sreenivasan et al. 2013). Recently, a prospective plastic compressed electronic packaging material has been demonstrated that was produced using hand lay-up and vacuum infusion technique, where kenaf fiber was used as a natural fiber source with the polyester as a polymer matrix (Atiqah et al. 2020). To limit the water uptake properties of the composite material, micro-sized Alumina Trihydrate (ATH) was utilized that also enhanced the mechanical properties of the composites with respect to those of the packaging material that was not treated with the ATH (Atiqah et al. 2020). On the other hand, the effects of alkali treatment and stacking sequence on the properties of the Kenaf/epoxy composites were evaluated by Fiore et al (Fiore, Di Bella, and Valenza 2015). The fabrication process includes the pre-treatment of the fibers with an alkaline solution (6% wt. of NaOH for 48 hours and 144 hours) at room temperature, hand lay-up process was followed by polymerization of the matrix in a flexible bag at negative pressure reached via a vacuum pump, curing at ambient temperature for 24 hours, and post-curing step was accomplished at 60°C for 8 hours. The authors revealed that the fibers treated for 48 hours led to better results by removing the fiber impurities from the fiber surface. However, the longer exposure time of NaOH on the fibers damaged the fibers (Fiore, Di Bella, and Valenza 2015). From other studies of the fabrication of kenaf/epoxy composites, it has been found that when the kenaf fibers those are longer in length, are treated for 48 hours by keeping them in straight direction showed excellent mechanical properties compared to the randomly arranged smaller fiber-based composites, which supports the other similar results reported in the literature (Radzuan et al. 2020; Sapiai et al. 2020).

Application of bast fibers reinforced polymer composites

The bast fibers reinforced polymer composites are now widely used in multiple application areas ranging from the agricultural fields to the latest automotive, because of their outstanding natural and technical properties (Aji et al. 2009; Begum, Fawzia, and Hashmi 2020; Keya et al. 2019). Moreover, as these fibers are biodegradable and abundantly available in nature, both industrial and academic researchers are trying to utilize these fibers for the development of fiber-reinforced composites to ensure a green environment for the next generation (Kim and Cho 2020; Kumar et al. 2019). The detailed application areas of all the bast fibers are summarized herein.

Flax is one of the stronger fibers available abundantly in nature and its composites possess mechanical properties as similar as the glass fiber reinforced polymer composites (La Mantia and Morreale 2011; Muzyczek 2020; Yan, Chouw, and Jayaraman 2014). Hence, these composites are widely used in the production of various automobile parts such as car body parts, door panels, headrests, glove-box, etc (La Mantia and Morreale 2011; Muzyczek 2020; Yan, Chouw, and Jayaraman 2014). Some other potential usages of flax fiber-based composites are flax reinforced snowboards, tennis racket, and bicycle frame which are fabricated with the combination of flax fibers and carbon fibers (25:75 and 80:20), respectively (Sen and Reddy 2011). In these composites, the flax fibers exhibited superior performance compared to the carbon or glass fibers. Apart from these, the flax fibers-based composites have their end uses in producing tiles, flowerpots, marine piers, fishing rods, racing sails, boats, laptop cases, and furniture items (Sen and Jagannatha Reddy 2011; Syduzzaman et al. 2020). The automobile is the major sector where the composites produced from the hemp fibers are used abundantly at several places of a car, for example, at the door panels, trim, roof, panel board, sunshade, window frames, floor coverings, and at the hardtop (Faruk and Sain 2015; Syduzzaman et al. 2020; Yan and Chouw 2013). Additionally, these composites were used in the fabrication of the surfboard, boats, bicycle path, chipboards, and dinghy (Subramani et al. 2017). The hemp fiber-based polymer composites are also extensively used in the alternatives of wood to produce furniture and flooring materials, geo-textile items, electrical products, paper, and packaging supplies, building and construction items, decorations, marine, cordage, banknotes, and pipes (Sullins et al. 2017; Väisänen et al. 2018). Composites made of jute fibers are feasible to apply for the housing, roping, domestic, packaging industry, furniture, and kitchen cabinets (Faruk and Sain 2015; Kumar et al. 2019). Owing to the excellent technical properties and abundancy in nature, researchers are trying to manufacture jute fiber-based composites materials for the automobile and footwear industry, construction and building industry, decoration, false ceilings, roof covering, furniture, geo-textiles, wall partition, door and window panels, prefabricated sheds, packaging, textiles, and protective clothing, and baby toy industries (Fonseca et al. 2019; Sanivada et al. 2020). Ramie fiber-based composites are broadly used in the fabrication of bulletproof panels with epoxy resin at a lower manufacturing cost and lighter in weight than that of the traditional ballistic protection equipment used in the military (Marsyahyo et al. 2009; Mujiyono, Nurhadiyanto, and Mukhammad 2017). These panels can successfully resist level II high impact of a projectile, which was determined using the National Institute of Justice (NIJ) standard. This might be due to the presence of excellent breaking strength and toughness of the composite panels (Nurhadiyanto et al. 2021). These results are better compared to the traditional ceramic plate, Kevlar/aramid composite panels, and steel-based ballistic materials (Nurhadiyanto et al. 2021). Apart from this, socket prosthesis, civil building and construction materials, electrolytes, packaging materials, industrial sewing threads, fishing nets, and laminated industrial aluminum sheets are also some of the examples of the application of composites (Du, Yan, and Kortschot 2015; Sen and Jagannatha Reddy 2011). Another type of bast fiber, Kenaf has both the economic and ecological benefits that can be accumulated greater proportion of carbon dioxide and therefore, photosynthesis rate of this fiber plants is much higher than any other plants, which can assist in avoiding the deforestation by planting more kenaf trees (Aji et al. 2009; Lam, Hori, and Iiyama 2003). Kenaf fiber-based composite can be used for the automobile industry to make prototype headliners with 50% lower weight compared to traditional headliners (Chen et al. 2005). Other major potential applications of kenaf fiber-based composites are rope, twine, cordage, engineered wood, sails, bags, fabrics, mobile cases, animal beddings, fast food wrappers and containers, automobile interior lining, ceiling, furniture, oil and liquid-absorbent, biomedical and bioengineering applications, socket prosthetic, package trays, door panel inserts, aircrafts side-walls and ceiling panels, low load-bearing parts, roofing panels, insulation boards and beams in construction, and and in developing external body parts for cars (Davoodi et al. 2012; Namvar et al. 2014; Pang, Shanks, and Daver 2015; Radzuan et al. 2020; Syduzzaman et al. 2020).

Conclusion

From this extensive and precise review, it can be concluded that bast fibers possessed several excellent physicomechanical properties that are better or comparable to their synthetic counterparts. Moreover, these fibers are biodegradable, lightweight, sustainable, eco-friendly, renewable, cheap, and abundantly available in nature those eventually made these fibers an exceptional candidate to produce the fiber-reinforced polymer composites for the diversified applications to outweigh the use of the petroleum-based synthetic fibers, which are hazardous, costly, and non-renewable. Hence, the classification, properties, and possible application areas of the composites including their fabrication process have been discussed. It has been found that the bast fiber-based composites are extensively used in the automobile, building and construction, domestic, and packaging sectors. However, we need to focus on other application areas such as biomedical, drug delivery, bones and prosthesis manufacturing, and marine, where the use of oil-derived synthetic fibers and their composites are still dominating. Although most of the composites are fabricating using virgin bast fibers, researchers need to emphasize the use of waste and recycle bast fibers, which not only reduces the production cost of the composites but also accelerates the consumption of the waste bast fibers that are directly thrown into the landfill, to support waste management and sustainability.

Highlights

- The detailed classification of the bast fibers and their physical, chemical, and mechanical properties have been reviewed thoroughly.
- A detailed review of the greener applications of the composite materials fabricated using the bast fibers with both the thermoplastic and thermosetting polymers has been discussed.
- This review has demonstrated that there is a great potential for the abundantly available natural bast fibers to be reinforced with synthetic polymers to produce bast fiber-reinforced composite materials and used in diversified application areas to support the sustainability of the environment and the planet.

Disclosure Statement

The authors declare no conflict of interest.

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