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Recent Advances in Green Composites and Their Applications

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Abstract

Conventional petroleum-based toxic and non-biodegradable composites in comparison with natural fiber composites and hybrid natural fiber composites find attraction in the automobile industry, manufacturing, aerospace, sporting goods, construction, and marine applications due to the lower ecological risks. As global communities expand, the sustainability of our material systems is becoming increasingly important. Material producers are increasingly addressing issues like emissions of greenhouse gasses, embodied energy, toxicity, and resource depletion. The thrust to use eco-sustainable green composites is increasing due to their green marketing, newer recycling policies, societal impact, and improvements in cognitive values. Green composites have the challenge of replacing conventional materials like steel, wood, and non-biodegrading polymers. Specific material features of green composites for particular loading and load-bearing applications are reviewed including the properties and performances of various potential biopolymers and natural reinforcement elements. The applications of green composites in short lifespan products, sporting equipment, and the biomedical field are highlighted with detailed examples.

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1. Introduction

Composites are defined as two or more components with different properties that remain separate and distinct within one unity.[1,2] With one phase in the dimension of less than 100 nm, the composites are defined as nanocomposites.[3-6] Nanocomposites have shown unique properties and various applications involving environmental, energy, device, *etc*.[7-11] In recent years, green composites have been developed from renewable sources.[12-14] The thrust to use eco-sustainable green composites is increasing due to their green marketing, newer recycling policies, societal impact, and improvements in cognitive values.[15] The green composite materials are being designed and fabricated to replace conventional products sustainably and responsibly in automobile, aerospace, sporting goods, construction industry, and marine applications.[16,17] Green composites are products made of renewable feedstock from agriculture and forestry, including crops and agricultural by-products and their residues. Natural fibers, which differ according to their origins, are generally classified as minerals, lignocellulosic, and animal.[16-18] The most prevalent animal fibers are silk and wool, which are commonly used in textile industries.[19]

Vegetable fibers can be extracted from several different parts of the plants, particularly leaves or bast. Bast fibers, especially hemp, flax, and kenaf, due to their properties and availability, are considered the most promising.[16,18,20] With increasing industrial demand for vegetable fibers, the low production levels have difficulty meeting the demands. The number of by-products has increased from commodity crops that are inexpensive and sustainable for the manufacture of fibers. Several by-products consist of cellulose extracted in the fiber form and are considered as possible composite fillers.[16,20] Moreover, renewable green composites incorporating renewable natural fibers with appropriate properties are more promising for companies, environments, and end customers because of the diminishing oil resources. As global communities expand, the sustainability of our material systems is becoming increasingly important. Material producers are increasingly addressing issues like emissions of greenhouse gasses, embodied energy, toxicity, and resource depletion.[18,20,21]

This review explores and addresses the current

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developments in natural fiber-reinforced polymer-based green composites and offers insights into their commercial applications. Meanwhile, the lack of consistency in the standards of pre-processing, treatment, storage, and post-processing processes of natural fibers, contributes to the difficulties of selecting both suppliers and consumers. A review of the various mechanical properties of natural fibers, their applications, and future trends is presented to address the precarious scenario.

1.1 Natural fibers

In general, natural fibers are either vegetable or animal-based. The vegetable fibers are mainly cellulose, and the animal fibers are protein.[22] Natural fibers have relatively complex cell structures, with every fiber being part of rigid microfibril cellulose, embedded in a hemicellulose matrix and soft lignin. The composite fibers such as abaca, kenaf, hemp, and flax have been highly investigated. The abundant jute and stiff ramie fiber have recently been highlighted.[23] Fig. 1 illustrates annual production volume data per facility for several types of fibers. Jute is one of the world's most abundant fiber crops with excellent mechanical performance. In contrast, flax is one of Europe's most essential and demanding bast fibers. In France, Belgium, Spain, the UK, and the Netherlands, approximately 80% of the world's total flax crop is grown. Flax is comparatively stronger, crisper, and rigid in handling.[24-26]

In a comparison with the properties obtained by characterization of commonly used potential natural fibers by previous researchers, ramie fiber used as a reinforcement in the bio-composite demonstrated improved performance.[16] Hence, Ramie proves to be one of the most durable textile fibers and has a strong potential as polymer composite reinforcement.[20] The properties such as density, diameter, young's modulus, and tensile strength of several natural fibers are shown in Table 1.

applications. The mechanical properties are critical deterrents to the generalized use of natural fibers in various industrial

1.2 Biopolymers

Biodegradable biopolymers are widely ranged including both thermosetting and thermoplastic polymers and originate from various renewable sources. Nevertheless, these thermosets are not 100% natural products if polymerization with synthetic monomers.[27,28] The current status of thermosetting and thermoplastic biopolymers is discussed to illustrate their respective biodegradability.[29]

The use of bio-thermoplastics in green composites is quite common and these include polyhydroxy butyrate (PHB), polylactic acid (PLA), and polysaccharides of plant origin. The extremely widely used matrix for green composites is the thermoplastic starch, comprised of both linear regions forming helical structures and branched regions. Biopolymers also include proteins like albumin and collagen (gelatine). Different types of biopolymers with their properties such as density, young's modulus, tensile strength, and elongation at break are illustrated in Table 2.

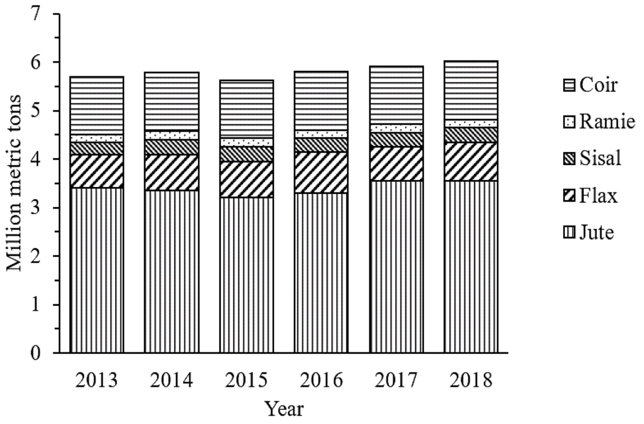

Fig. 1 Growth per fiber in volume per year for Coir, Ramie, Sisal, Flax, and Jute.

Table 1. Properties of potential natural fibers used in the development of green composites.

Fibers	Diameter (mm)	Density (g/cm³)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	Price ($/Kilo)[25]
Flax	40-600	1.5	345-1500	27-39	2.7-3.2	3.11
Hemp	25-250	1.47	550-900	38-70	1.6-4	1.55
Jute	25-250	1.3-1.49	393-800	13-26.5	1.16-1.5	0.925
Kenaf	2.6-4	1.5-1.6	350-930	40-53	1.6	0.378
Ramie	0.049	1.5-1.6	400-938	61.4-128	1.2-3.8	2
Sisal	50-200	1.45	468-700	9.4-22	3-7	0.65
Curaua	7-10	1.4	500-1100	11.8-30	3.7-4.3	0.45
Abaca	10-30	1.5	430-813	31.1-33.6	2.9	0.345
Bamboo	25-40	0.6-1.1	140-800	11-32	2.5-3.7	0.5

Table 2. An illustration of the physical properties of different types of biopolymers of PLA, L-PLA, DL-PLA, PGA, PCL, PHB, and starch.

Types of biopolymers	Density (kg/m3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	*T*m (◦C)	*T*g(◦C)
PLA	1210	21	0.35	2.5	150	45
L-PLA	1240	15.5	2.7	3	170	55
DL-PLA	1250	27.6	1	2	am	50
PGA	1500	60	6	1.5	220	35
PCL	1110	20.7	0.21	300	58	-60
PHB	1180	40	3.5	5	168	5
Starch	1390	5	0.125	31	110	am

1.3 Less-common natural fiber-reinforced composites

Except for the widely studied natural fiber-reinforced composites, even less common natural fibers have been incorporated to make reinforcing polymer-based composites. For example, Fortunati *et al*. introduced the okra short fibers into a PLA matrix with loadings ranging from 10 to 30 wt%.[30] The effect of alkaline treatment has been studied on the mechanical and thermal properties of the resulting composites. The morphological studies of the treated composites showed that this chemical process induced a decreased fiber diameter. An X-ray profile emphasizes the appearance of undetected cellulose II in the non-treated composites. These studies confirmed that the alkaline treatment removed the non-structural substances in okra fibers and increased the cellulose's stability.

The inclusion of fibers, even after the chemical treatment, resulted in lower stress and young module values compared to untreated composites. They demonstrated a higher stiffness value of the obtained composites compared to neat PLA. Due to the presence of untreated and treated alkali fibers, there is an increased degradation rate in the PLA matrix because of hydroxyl groups. This increase suggests that the natural fibers would be handy to the environmental effect at the end of their lifetimes, and could lead to an accelerated weight loss of PLA. To manufacture fully biodegradable starch-based composites using urea-formaldehyde as a cross-linking agent, okra fiber was also used in the range of 5 to 25% by weight as particle fillers having average sizes equal to 90 mm.[31] The biodegradation studies of the matrix and composites were performed using the soil burial method, showing that the rate of degradation decreases with the increased fiber amount due to the lower okra fiber degradation rate compared with the corn starch.

Sudhakara *et al*. investigated the thermal, mechanical, and morphological characteristics of polypropylene (PP) composites reinforced with 5% fine fibers of both alkaline and untreated Borassus.[31] The properties of the resulting composites were assessed using polymer maleic anhydride grafted polypropylene (MAPP) as a compatibilizer. The thermal stability of treated alkaline composites was improved in the presence of MAPP compared to other composites. Adding MAPP reduced the absorption of water significantly and increased the mechanical characteristics of the composites. Fourier transforms infrared spectroscopy showed that the mechanical characteristics of the composites were also enhanced by the chemical bonding between modified Borassus and HDPE fibers. Besides, it was found that the thermal stability was also slightly improved for the modified HDPE composites. Moreover, in addition to glass fibers of the same length, Velmurugan and Manikandan used short Borassus fibers of 50 mm to create two polyester hybrid composites.[32] The former was formed by spontaneous mixing of glass fibers and Borassus while the latter was by Borassus between two glass fiber layers. The composites with a total fiber weight of 55% were made particularly with varying amounts of Borassus fiber and glass. As presumed, the composites demonstrated improved mechanical properties and decreased moisture absorption by increasing the fiber content of the glass.

The thermal properties, moisture absorption, and mechanical properties were studied for the polypropylene composites with an alkaline treated Borassus fiber loading of 5, 10, 15, and 20 wt%. The mechanical properties of polypropylene composites with 15 wt% Borassus fibers were found to be comparable to composites with sisal and jute fillers and higher than the composites with coir fillers. The residues of the Borassus and coir were higher in the thermal gravimetric analyzer (TGA) at 500 °C due to the high lignin content and less water intake than sisal and jute (Fig. 2).

The last few years have seen developments in polymeric composites enhanced by lignocellulose fibers from plant leaves such as *Sansevieria cylindrica* and *Sansevieria ehrenbergii*. The first attempt was made by Sreenivasan *et al.* to reinforce the polyester (PS) matrix using *Sansevieria*

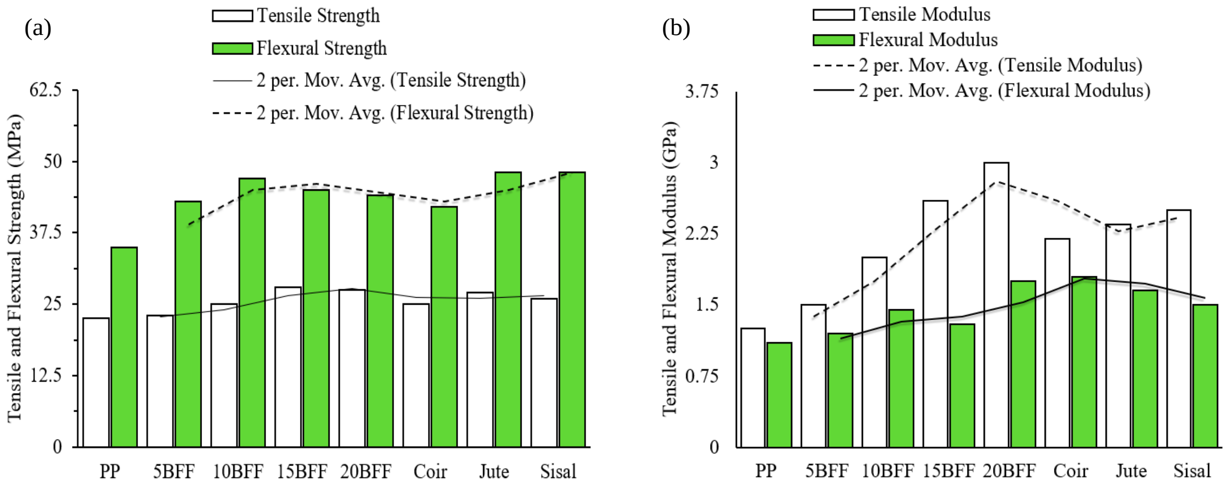

Fig. 2 (a) Tensile and Flexural strength (b) Tensile and Flexural modulus. Reproduced with the permission from [31] Copyright 2012 Wiley Periodicals, Inc.

cylindrica raw, randomly oriented short fibers.[33] In particular, the mechanical properties of the resulting composites were investigated in terms of fiber length (*i.e.* 10-50 mm) and weight amount (*i.e.* 10-50%) on the mechanical properties (*i.e.*, tensile, flexural, and impact) of the resulting composites, showing that their efficiency was improved by up to 40% of fiber content and 30 mm of fiber length. As studied and reported by Sreenivas *et al.*, the fiber critic length (30 mm) and the optimal fiber weight content (40%) were chosen to manufacture composites with various fiber chemical treatments (*i.e.*, alkali, benzoyl peroxide, potassium permanganate, and stearic acid).[33] Several studies have shown that untreated Sansevieria cylindrica fiber (USCF), Alkali-treated SCF, Benzoylperoxide-treated SCF, Potassium-permanganate-treated SCF, and Stearic-acid-treated SCF samples were examined for the surface morphological behavior of chemically treated SCFs using JEOL model 6390 SEM with secondary electron imaging.[34] The best composite performance was achieved with potassium permanganate treatment even for the dynamic mechanical properties, whereas the fiber composites treated with benzoyl peroxide demonstrated the best thermal stability.

Wu et al. have produced a polyvinyl alcohol (PVA) composite reinforced with Nelumbo nucifera fibers, based on the composite structure of cocoon silk.[35] The following procedure was used to fabricate the composites (Fig. 3). It can be briefly stated as i) Motor 1, which rotates anti-clockwise, is fixed to the lotus stem, and the lotus fibers are rotating in a clockwise direction by motor 3; ii) simultaneously the PVA solution is sprayed in small droplets from the nozzle 2 and are deposited on the fiber bundles, and iii) the stick 4 collects the composite continuously. As the green composite fiber is based on the lotus stem diameter, the lotus stems have been selected with the same diameters as shown in b). The composites were mainly produced at various PVA loads of 10.4, 22.4, and 37.3%, consequently establishing a twisting angle of 20 degree for the bio-inspired composites. The tensile strength of lotus fiber composites was similar to that of the flax fibers; however, it was much more sizable than other commercial natural fibers and cocoon silk.[36] Moreover, it was found that

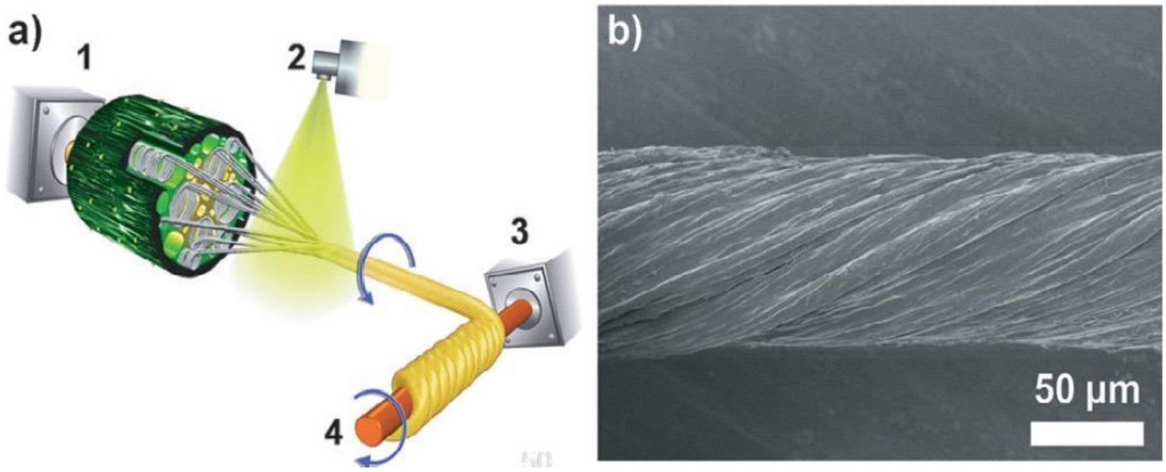

Fig. 3 a) Experimental illustration of the fabrication of the bio-inspired lotus fiber, and b) scanned electronic microscope image of lotus fibers having a diameter of ~ 80 mm. Reproduced with the permission from [35] Copyright 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

Their specific modulus is thrice as high as that of cocoon silk. As reinforcements of polyurethane (PU) and epoxy resin in a wide variety of naturals, Oliveira, and D' Almeida used natural fibers from the *Manicaria saccifera* palm tree, to improve the composite materials.[37] Several other lignocellulose polymer reinforced polymer matrix composites are comparable in flexural and compressive properties to *Manicaria Saccífera*, fiber-reinforced epoxy, or polyurethane matrix composites. Further, the epoxy matrix was found to promote a better interface with the Manicaria natural fabric than polyurethane. The Taguchi technique was used as an experimental design method to analyze the effects on the tensile properties of biocomposites laminae by various processing parameters, including compression mouldings parameters, fabric chemical processing parameters, and the fiber content ratio.[38] A graphical summary is provided in Fig. 4 on the strength, stiffness, specific strength, and specific stiffness compared with glass fiber-reinforced plastics. It is clear that, even though the absolute strength is lower than that of synthetic counterparts, the specific strength and stiffness are equivalent to those of glass fiber-reinforced composites.[39] It should be remembered, however, that the tensile properties of different composites reinforced with less common natural fibres are in close alignment with those of composites produced from other natural fibres, as presented by earlier researchers (Table 3).

2. Attributes of green composites

2.1 Mechanical properties

Mercerization-fiber alkali treatment is an effective and standard method to reduce water absorption and enhance fiber/mattress adhesion. This method enhances the ability to interact between matrix and fiber chemically and thus enhances the mechanical interlocking by employing rougher topography and a more extensive range of fibrils.[40] The mechanical performance of natural fibers PLA, L-PLA, DLPLA, PGA, PCL, PHB, and Starch is shown in Fig. 5. Hemicellulose was dissolved during the treatment, and the hydrographic part of natural fabrics contributed little to the strength.[41] In an alkaline treatment research work, the tensile strength of phenolic composites was improved by 52% after the treatment.[42]

Weyenberg *et al*. have investigated the results of chemical treatment on a unidirectional flax composite. An average in crease in the strength of 30% was found in the material fiber direction, while an increase of 138% was found in the transverse (matrix-dominated) direction.[40] This significant increase in the matrix-dominated property, compared with the direction of the fiber, indicates that chemical treatment primarily influences the bonding of fiber/matrix. Table 3 tabulates the mechanical properties of less common natural fibers composites compared to various other natural fiber-reinforced composites.

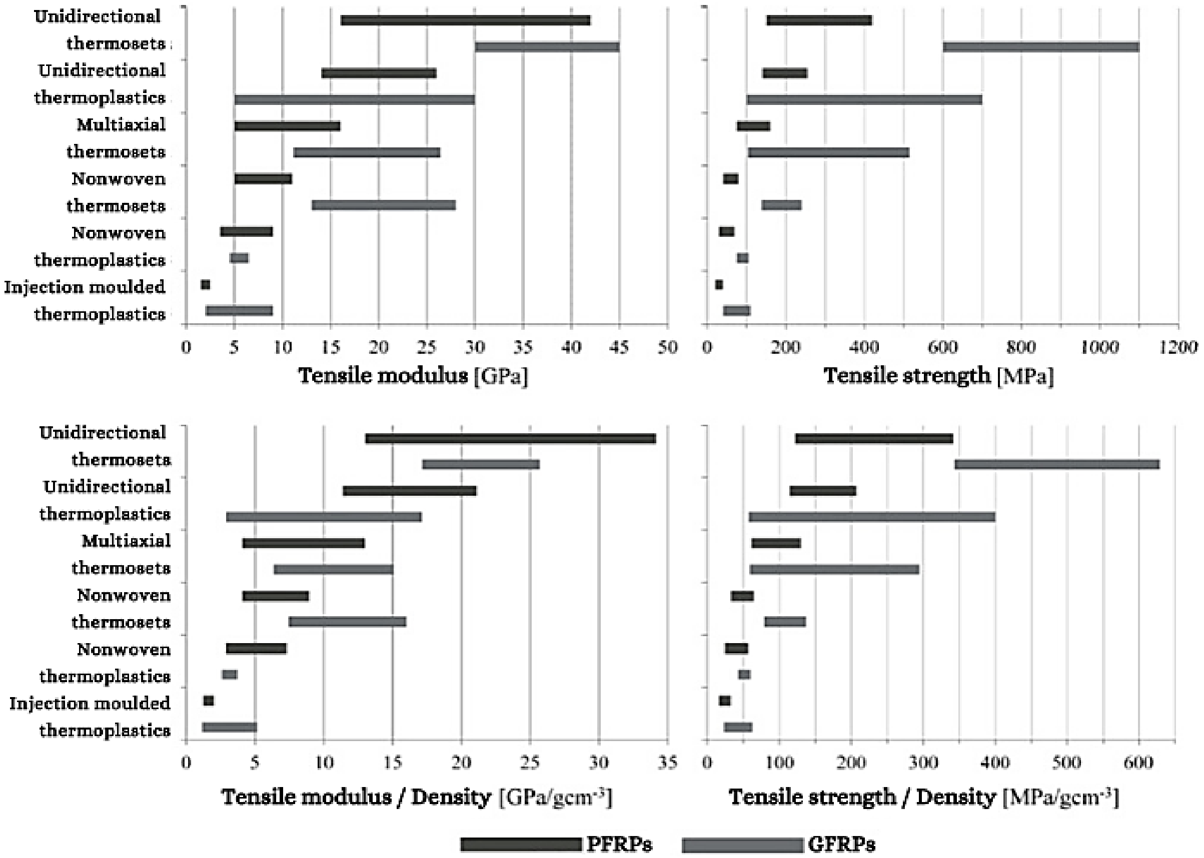

Fig. 4 A graphical comparison of E-glass reinforced plastics (GFRPs), of the tensile strength and modulus with plant fiber reinforced plastics (PFRPs). Reproduced with the permission from [39], Copyright Elsevier Ltd.

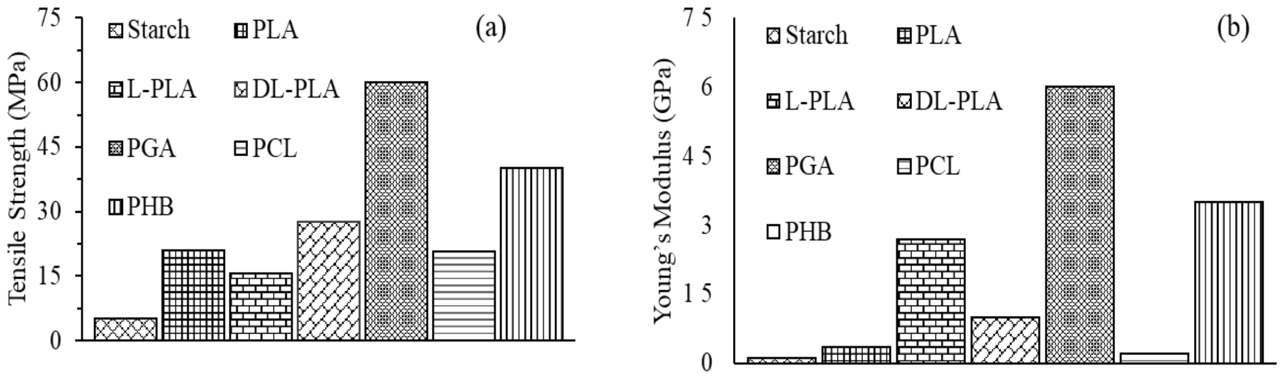

Fig. 5 Mechanical performance of natural fibers PLA, L-PLA, DL-PLA, PGA, PCL, PHB, and Starc (a) Tensile Strength (b) Young's Modulus.

Table 3. A comparison of the mechanical properties of uncommon natural fibers with various other natural fiber-reinforced composites.

Fiber	Matrix	Fiber content (%)	Tensile strength (MPa)	Young's modulus (GPa)	Notes	References
E-glass (unidirectional)	PP	35 (v)	700	26.5	Compression moulding	[43]
E-glass (3D-random)	PP	30 (w)	49	2.2	Injection moulding	[44]
Sisal (unidirectional)	Epoxy	50 (v)	-270	-9	Compression moulding/untreated	[45]
Sisal (Random)	Polyester	30 (v)	24	5.3	Vacuum infusion/untreated	[46]
Sisal (Random)	Acrylic	30 (v)	31	3.4	Vacuum infusion/untreated	[46]
Flax (unidirectional)	Epoxy	40 (v)	133	28	Autoclave/untreated	[40]
Phormium tenax (unidirectional)	Epoxy	55 (w)	223	16.8	Compression moulding/untreated	[47]
Flax (2D-random)	Epoxy	22 (v)	60	9.2	Autoclave moulding/alkali treated (1%)	[48]
Flax (3D-random)	PP	30 (w)	27	1.7	Injection moulding/untreated	[49]
Hemp (unidirectional)	PP	42 (v)	215	21.1	Compression moulding/untreated	[50]
Hemp (3D-random)	PP	30 (w)	30	1.5	Injection moulding/alkyl ketene dimmer	[44]
Okra (2D-random)	Starch	25 (w)	2.21	0.24	Compression moulding/untreated	[51]
Okra (3D-random)	PLA	30 (w)	58.8	4.6	Injection moulding/untreated	[30]

Continued

Borassus fine fibers (3D-random)	PP	15 (w)	28	2.5	Injection moulding/alkali treated	[31]
Borassus fine fibers (3D-random)	HDPE	20 (w)	20.1	0.53	Injection moulding/untreated	[52]
(Borassus fibres 2D-random)	Polyester	54 (w)	39.30	1.43	Compression moulding/untreated	[32]
Arundo donax (3D-random)	Epoxy	15 (w)	37.5	3.04	Casting	[53]
Arundo donax (2D-random)	Polyester	40 (v)	16.35	2.37	Compression moulding/untreated	[54]
Arundo donax (2D-random)	PLA	10 (w)	37.3	3.85	Extrusion+compression moulding	[53]
Artichoche (2D-random)	PLA	10 (w)	21.9	3.4	Compression moulding	[55]
Artichoche (unidirectional)	PLA	10 (w)	50.0	4.4	Compression moulding	[55]
Isora (unidirectional)	Epoxy	51 (v)	200	6.5	Compression moulding/untreated	[56]
Isora (2D-random)	Polyester	24 (v)	36	1.6	Compression moulding/untreated	[56]
Isora (unidirectional)	Polyester	45 (v)	190	7.6	Compression moulding/untreated	[56]
Isora (3D-random)	Natural Rubber	15 (w)	14	2.71	Two roll mixing/untreated	[56]
Grewia optiva (2D-random)	Polyester	30 (w)	25	-	Compression moulding/untreated	[57]
Grewia optiva (2D-random)	Phenol-formaldehyde	30 (w)	36.34	0.74	Compression moulding/untreated	[58]
Napier grass (unidirectional)	Polyester	31 (v)	118	2.17	Compression moulding chemically extracted (NaOH)	[59]
Napier grass (2D-random)	Polyester	25 (v)	15.64	3.02	Compression moulding/untreated	[60]
Cissus quadrangularis (2D-random)	Polyester	40 (w)	33.41	1.84	Compression moulding/alkali treated (5%)	[61]

2.2 Fiber properties

Natural fibers, due to their origination from natural sources, tend to suffer from natural variations in properties, including fiber type, length of the fiber, and chemical composition of the fibers. A few factors that lead to the inconsistency in these properties include fertilization, the density of the seed, variations in crop type, field location, soil quality, climate, and harvest and fiber location on the plant.[62] is a significant challenge that must be overcome for structural applications of such materials, in which failure could be undesirable and hence has to be reliably forecasted. There have been attempts to model the tensile properties, size, and shape by analyzing the individual fiber statistical analysis. However, few consider the modeling of lamina and laminates, where three-dimensional discontinuities such as microbeads may cause variation. The fiber length and the fiber direction should be maximized with the applied load to effectively utilize the properties of the fibrous composites. Better fiber alignment also makes it possible to achieve higher fiber volume fractions.[63]

2.3 Renewability

Most of the traditional materials in the polymer matrix are obtained from petroleum that is non-renewable in 10^6 years but is typically converted into CO_2 in 1-10 years if consumed as fuel or plastic.[64] This aspect is a significant motive for adopting green composites, where both matrix materials and reinforcement are derived from plants.[64] This is how renewable use contributes substantially to the development of carbon-neutral materials by balancing the rate of CO_2 rate at the consumption rate.

2.4 Biodegradability

If the materials can be degraded by living organisms, they are classified as biodegradable.[36] Natural fibers are biodegradable, like many polymers, whose degradation rate is determined throughout the backbone by chemistry.[65] For polyesters and polyanhydrides, for example, the degradation happens both through hydrolysis at considerably different rates, *i.e.*, 3.3 hours and 0.1 years, respectively.[66] Polyethers, are a class of polyarylenes linked through varying sequences of ether (E) and ketone (K) units. Depending on the prevalence of one of the two units, these polyarylenes can be rich in ethers (*e.g.*, poly (ether ether ketone) (PEEK)), ketones (*e.g.*, poly (ether ketone ketone (PEKK)), or balanced (*e.g.*, poly (ether ketone) (PEK)), are known to be non-biodegradable because of the absence of a hydrolyzable bond. This property can be tuned for application by making copolymers from polymers with various stages of degradation.[38]

Because of this economic transition and the adjustment to inflation, for example, the price of PP was increased by 111% Biodegradation is a desirable feature because it hinders the piling up of solid waste. This feature is typically essential in composite materials and prevents their use in limited-life products.[35] Green composites may enable these composite materials to reach new markets as they have a significant advantage over synthetic composites.

2.5 Low cost

Natural fibers carry a cost advantage when compared to synthetic fibers. The cost of biopolymers was considered in the year 2000 to be too high to support the industry.[20] The oil prices have increased since then, the manufacturing methods of biopolymers have been improved and the price of PLA was decreased by 73%.[20] While work on improving the properties of biopolymers is continuing, the cost efficiency of green composites merely depends on the fraction of fiber volume used. The North American natural fiber market is expected to rise to 1.38 billion USD by 2025 from 155 million US Dollars in 2000.[64]

2.6 Water absorption in high natural fiber

Cellulose is a hydrophobic molecule imparted to the natural cellulose fibers in three alcoholic groups per glucan repeating unit.[20] The water absorption of the finished composite material is, however, another outcome. Water absorption causes fiber swelling which leads to delamination, surface roughening and a subsequent loss of strength of the material reported at up to 31%.[62] Masoodi and Pillai found that water absorption was stabilized at 17.5% for 40% of compounds of jute and epoxy, and when a bio-derived epoxy was used, the value was instead jumped to 26%.[67] Symington *et al.* examined the effect of moisture on the mechanical properties of natural fibers.[68] This study found that moisture plays a vital role in affecting the mechanical properties of natural fibers. Whilst the tensile strength of fibers such as kenaf, jute, and abaca center around similar values when at room temperature/humidity conditions compared to being fully soaked, fibres such as flax and coir undergo a notable decrease. Hemp was considerably degraded and hence could not be tested, and its stability raised concerns under different environmental conditions.

Chemically modifying their surface is found to improve the properties of natural fibers. For example, alkaline treatment, used for almost all-natural fiber with positive results, is the most common and reliable chemical alteration process to minimize moisture absorption.[20,69] The exposure of fibers to alkaline solutions like KOH and NaOH causes a non-cellulosic cementing substance to dissolve. For example, lignin and hemicellulose reduced moisture absorption through the fiber.[68] Duralin process is an alternative to the alkaline treatment, which is more environmentally friendly as it makes the use of steam to degrade and remove lignin and hemicellulose. The analysis of flax fibers recorded the maximum moisture contents of an untreated sample after exposure to 100% humidity at 14.33% compared to 42.58% for a Duralin-treated sample.[70] Other advantages of Duralin are the improvements in the fiber's stability, such as dimensional and temperature stability, improvement in resistance to fungal attacks, and improvement in the fiber's mechanical properties. However, the required high temperatures add considerable energy costs to the material, which once more compromises the environmental credentials of green composites.

2.7 Poor durability

Similar to biodegradable materials, green composites have minimal longevity. Environmental exposure can lead to quick material degradation. Forecasting the life of green composites is a significant obstacle to their extensive usage.[64] The development of fungus and bacteria is one of the reasons for the degradation of green composites. For example, Stamboulis and Baillie witnessed a growth of fungus in the flax fibers after three-day exposure to moisture.[70] Singh and Gupta show that weathering over two years of a jute/phenolic composite resulted in color fading, resin cracking, bulging, fibrillation, and black spots.[71] A rainbow fungus was exposed to a composite of bagasse/polypropylene in the work of Nadali *et al*., after four months, the bending modulus, strength, and hardness were reduced by 30-50%.[72]

2.8 Degradation of fibers at elevated temperatures

Natural fiber will be degraded at temperatures higher than 170 °C, which will reduce the number of applications, matrix systems, and processing methods.[64] However, this degradation property was not proven to be a restricting factor in the production of green composites with a bio-derived polymer matrix like PLA, since these materials were processable only at low temperatures.[62]

3. Matrix material

Different renewable materials can also represent promising candidates in a biodegradable, or non-biodegradable green composite. The main problem now is the extent of recycling and degradation when it is disposed of. There are potential ways to use incineration to recover energy even when the material cannot be recycled directly for a supposed 100% composite that is bio-based. When incinerated, there is no gas produced by decomposition, and there are no emissions of harmful gases.[73] First, traditional thermosets cannot be easily recycled from the whole product. Traditional thermoplastics, conversely, possess processing constraints, for instance, high viscosity for injection molding. The new bio-based thermosets are challenging to be recycled or reused, similar to synthetic thermosets, but most can later be decomposed.[20] From vegetable oils, thermoset polymers are typically formed through cationic polymerization with other monomers like cyclopentadiene, divinyl benzene, and styrene. In the presence of latent thermal catalysts or anhydrides, in other instances, epoxidized oils are converted as curing agents to initiate the polymerization directly. Some polymer networks may also be biodegradable in the soil.[27] These additives are non-renewable and synthetic and thus do not contribute to the overall green composite production. The implementation of bio thermoplastic, which does not require the polymerization process and combines the benefits of recycling and prospective disposal, would also be preferable.

4. Bio-based resins as matrices

Bio-resins are obtained from biodegradable or compostable biological sources and can be disposed of and decomposed hypothetically after use. Concerning decomposition, it is relatively troublesome to use it on the surfaces of A-class finish surfaces without careful processing or coating, when considering long-life applications. That also may occur in natural fibers as they may degrade even in synthetic resins due to the inevitable void content of the composite. Another significant disadvantage is the high cost of these resins, which renders them unaffordable even to large-scale manufacturers. Low heat distortion, low melt viscosity, brittleness, and high gas permeability are other disadvantages of bio-based resins that restrict their applications.[74]

Finally, there is a current debate as to whether such products are a more sustainable alternative to traditional plastics. The economic stability relations between societies could easily be disrupted by the potential transition from synthetic to bio-based dominant plastics. These adjustments include the replacement by the production of renewable resources of several specific raw materials, which are currently manufactured extensively from fossil or mineral resources.[40] The key point regarding the appropriate choice of materials would be that the composite produced must not comprise the materials from dietary sources. In the global food supply balance, edible plants, or any edible raw material may be the parts that can be removed from the food supply, *i.e.*, the human food chain, and leads to social unrest. Also, the bio-plastics industry must tackle the problem of whether bio-plastics will reduce fertile lands or increase incentives for reducing forest areas to create more significant agricultural lands.

The optimal amount of materials in the laboratory by microbial production is one way to deal with one of the future challenges, for instance, biotechnological fermentation processes. With the successful manufacture of renewable polyesters by the biotechnological processes, the production of lactic acid is currently on the market, and approximately 90% of them are concentrated in the same process.[40] However, during such processes, cheap raw materials should be further enhanced to compete with chemically derived materials.

Higher biological resistance has been achieved in biocomposite materials with bio matrices reinforced by natural fillers than in conventional polymer materials based on oil. This is due to the combination of conventional polymer properties (small weight and easy processing) with selective metal properties (high strength and toughness). The creation of biocomposites opens up a variety of possibilities for creating composites with a wide range of properties, which in turn allows for the formation of novel, multifaceted end-use products.

5. Contemporary applications of green composites

Green composites in the automotive and construction industries are often promoted for use. Green composites have quite a high potential in this industry because carbon could be stored easily for many years in those materials.

Furthermore, green composites can also enable the automotive industry to save weight and vibrational damping. However, the material properties necessary in construction and automobile fields do not often suit the attributes of green composites, which are currently obtained, except for non-structural and interior applications. Likewise, for the replacement of glass fiber reinforced polymers (GFRP), green composite characteristics may not make them a suitable replacement because their absolute mechanical characteristics are lower and also may be excluded from use for a wide variety of GFRP applications such as boats, kayaks, piping, and tanks due to their water absorption tendencies. Although design and manufacturing techniques can be modified to take full advantage of their excellent mechanical properties for the GFRP-intensive structural applications, even in wind turbine blades, large fiber property variability and low durability requirements will still hinder their use.

5.1 Automotive applications of green composites

In the automotive industry, moving towards more sustainable construction is an effort to make the environment safe, and economical, and demands European Union (EU) regulations. Some of these practices are regulated, but anecdotal evidence suggests that consumers demand enhanced environmental credentials to consume them. The latter plays a leading role in the sustainable use of materials.[16] Green composites are an emerging class of excellent environmental resources. In this research work, green composites are elucidated as biopolymers that are strengthened with natural fibers. Besides developing new sustainable materials, substantial improvement in the applications of existing green materials is needed to ameliorate the sustainability of our material systems. The applications of composites in automotive panels, as introduced by several automotive manufacturing industries that use renewable materials in preparing composites, provide yet another way of balancing sustainability and costs. Over recent years, efforts are made to minimize the use of expensive glass, aramid, or carbon fibers. Green composites are used as replacements in a wide variety of passenger and commercial vehicle interior parts to benefit from the lower density and the costs of individual natural fibers. Here are a few examples of green composites used in the automotive industry by various car manufacturers in the interior of their vehicles: (1) Mercedes Benz used an epoxy matrix in its E-Class cars in 1996 while using indoor jute panels.[18] (2) When Audi launched their 'Audi A2' in the year 2000, another paradigm for green composites was introduced where polyurethane reinforced door trims were made of mixed flax and sisal materials.[20] (3) In its 2010 Flex crossover, Ford recently adopted wheat paw for storage cup and in the inner deck, whereas BMW used a prepreg natural fiber mat and a unique acrylic thermosetting copolymer for the lower door panel for the 7 Series Sedan.[21]

However, it is more intricate to deal with the external components than the internal ones, as the external parts are subjected to varying weather conditions.[22] Mercedez Benz, in its Travego model, successfully replaced the conventional fiberglass-reinforced component with a part made of thermoset resin fiber and hemp. In the middle portion, a green composite was positioned between the headlights above a passenger bus's fender and tested its weather resistance.[23] Lotus used composite panels made of hemp fibers in dual-curve hardtops and spoilers in its ECO-Elise concept car launched in 2008.[24]

5.2 Short-span lifestyle products

Plastic cutlery and packaging, which are considered to have a limited life, are usually considered disposable products. Materials such as polypropylene (PP), polyethylene (PE), and polystyrene (PS) are heavily used in packaging. However, their non-biodegradability causes several environmental problems. The solution to this problem may be bio-composites containing a biodégradable polymer comparable to the cost and material performance of the commodity polymers.[20] Moreover, short life-span products are not only those items that we consider disposable, they are also items such as consumer electronics – for example, smartphones. For these products, design changes and technical advances will rapidly lead to an outdated product, although it remains functional. Although there is little research into product life, anecdotal evidence indicates that the obsolescence of goods is growing as customers are becoming more interested in the rapid growth of electronics, combined with a decline in product lifespans.[75] In a study in the United Kingdom from 1993-1998, computers, phones, radios, stereos, CD players, cell phones, pagers, and toys were found to have been six years or younger on average.[75] In recent times, the European Market Center-not due to a failure or expected obsolescence, but rather style obsolescence, recorded an average smartphone life of only 20 months.[76] Just 18 months before a battery failure, the same study found an average lifespan for the first, second, and third-generation iPods.[76] Like many modern consumer electronics designs, these products prove to be more economical in replacing the damaged sub-component rather than repairing them. Green mobile telephone credentials are an ever-growing development field. Sprint announced in January 2012 that it would have to comply with a minimum environmental standard for all to-be-sold mobile phones.[77] In June 2012, Juniper Research's report states that 392 million green handsets will be shipped by 2017, with a minimum recycled content of 50%, made without certain hazardous chemicals.[78] Mobile phones or electronics, in general, may also be an application of green composites because of their high obsolescence levels and minimal moisture exposure when being used. Toys are also a short life span application of green composites. While there have been no existing examples of green composite toys except wood toys, Springwood produces toys using cellulose-reinforced recycled plastics.[79] The use of products with enhanced environmental credentials in toying applications shows both the customer and company interests.

Green composites possess nontoxic attributes and can be desirable in producing toys for very young children. In short, consumer electronics and toys are perfect applications for green composites because of their low incarnation energy, biodegradability, and their low longevity as they make use of renewable energy sources.

5.3 Sporting equipment

Numerous features and limited absolute strength of natural fibers pose a challenge for their load-bearing applications. Another challenge to this type of application is maintaining its strength when formed into a composite material. The weight-specific properties of the fibers, such as stiffness, are excellent for being used and promoted for applications with substantial mechanical properties. Sports equipment is a decent starting point because the failure caused by material differences or degradations is less likely than more critical applications to cause severe injury or severe property damage. Nevertheless, sporting equipment applications to date have involved either the use of hybrid composites (natural and synthetic fibers combined) and/or non-biodegradable matrix polymers, negating one of the material's principal benefits – biodegradability. For instance, snowboards were strengthened with flax[80] and carbon-reinforced tennis rackets,[81] frames of bikes were reinforced with flax and carbon.[82] The flax fibers provide improved performance in such applications as they offer superior damping vibrations. This property leads to a better performance in navigating and moving snowboards that can handle rough terrain,[80] tennis rackets that provide extra support and comfort when the ball strikes the racket,[81] and bikes that withstand micron shocks for better comfort.[82]

5.4 Biomedical applications

Hydrophilic green composites allow for the hydrophilic surfaces to interact with substances as the live-cell tissue. This bioactivity characteristic identifies the green composites and their synthetic counterparts, along with their biocompatibility and biodegradability, for use as applications in the biomedical sectors. Linking up this area to composites would create materials that have significant advantages over widely used materials.[83] A few of the advantages are:

1. Toughness and strength (material properties) would be higher without any loss of weight.
2. Biodegradation kinetics and cell permeability could be adjusted with ease.
3. Nutrients and growth factors could be incorporated.[84]
4. Shapability.[85]

Tissue engineering has been known to be an interdisciplinary area, in which biomedicine has shown its advantages over green composites. The successful regeneration of articular cartilage was demonstrated by a highly customizable three-dimensional poly/collagen composite structure, particularly the scaffolds for soft tissue growth.[86] The biodegradation of poly(lactic-co-glycolic acid) (PLGA) can be adjusted easily using a monomer ratio.[86] Likewise, a customizable scaffold was developed by using both of these polymers in their homopolymer. A fibrous mesh of polyglycolic acid (GPA) has been integrated into a polylactic acid matrix. An improvement in the matrix proportion has been shown to result in both degradation rate and stiffness.[87] A successfully integrated *Gluconacetobacter xylinus* - bacterial cellulose, into a polylactic acid matrix, the material has been promoted for applications in the biomedical sector,[88] just like the cellulose composites.[89] Human mesenchymal stem cells may have been seeded onto a scaffold and can distinguish between a specific cell lineage for the growth of tissues or organs. This technique has been successfully used to grow trachea, and the subsequent transplantation proved to be ground-breaking because, unlike the standard transplant procedure, it provides an immunosuppressant-free life for the patient.[90]

Various factors, including the stiffness of the scaffold material, can affect the differentiation of the cells. Tissue growth can occur in vivo without the growth factor, with the differentiation bioactivity of green composites.[91] The bio-actively-chondrogenic distinction of Human mesenchymal stem cells (MSC) and the in vitro matrix deposition of cartilage was found to be caused by a silk and cellulose composite. Functional groups such as hydroxyl and amide were determined as essential and could be modified to the proportions of the two materials used.[92] In medical applications, biopolymers are already widely used, but only recently have natural fibers added to several systems to produce new green composite materials, offering distinctive functionality and performance.[93] This research is in its infancy, and with the right improvement, it will one day deliver medical treatments that are genuinely life-changing.

6. Challenges faced by green composites

The challenges faced by the green composites include the high cost of fabrication and raw materials are the major factors behind the cost of composites, weaker transverse properties, weaker and softer matrices, the function of which is to help the strengthening of materials, because which they have low toughness. Reusability or disposal of such composites is complicated, since few are partially degradable, and incineration is the only other form of disposal that has environmental consequences. Composites are difficult to attach compared to metals and contain two different materials bonded together which makes their repair and analysis difficult.

7. Conclusions and future prospects

This review highlights the material attributes, recent advancements of green composites, and their complementary applications. Furthermore, this review article delivers information and facts about natural fibers, biopolymers, and less common natural fibers reinforced composites. It provides a brief overview comparison of mechanical characteristics between uncommon natural fibers with various other natural fiber-reinforced composites. A concise summary of various attributes of green composites has been provided in this review. These include mechanical properties, fiber properties, renewability, biodegradability, low cost, water absorption, poor durability, and fiber degradation. The applications of green composites in the automobile industry and various complementary applications, including short-span life products, sporting equipment, and the biomedical industry, have been illustrated with detailed examples. Green composites can be used in many applications but they must be carefully aligned with the material to the application, as with all designs. While the properties of the green composites continue to be developed, care must be taken to ensure that these materials do not weaken their inherent green attributes.[94]

During the past couple of decades, numerous efforts have been made to improve the mechanical performance of natural fiber composites based on thermoplastics and thermosets, which have undergone significant growth in the automobile and construction sectors. Green composites have been applied to automotive body panels, as far as green composites have a mechanical performance comparable to that of synthetic composites. In contrast, green composites appear quite problematic because of their decomposability. The issue of biodegradability is a significant problem that must be considered be addressed when applications are targeting 100% bio-based composites, particularly in the structural components of exterior panels for future vehicles.

Another critical issue is the selection of fibers, and the existing possibilities provided by natural and renewable resources remain a long way to be explored. Compared with far more common natural fibers like sisal, hemp, flax, and jute, the comparison shows that further incorporation of new natural fibers into polymer composites has the potential with an outlook to increase natural reinforcement production and increase the use of natural fibers in new applications. Some of the less common natural fibers than conventional ones are not favorable, but can still be a cellulose nanocrystal source, which implies that their use will build an entirely new value chain for the crops. In conclusion, natural fiber composites are expanded, and their applications are certainly predicted to have a promising future. In this regard, natural fiber composites based on less common natural fibers may provide societal benefits from different perspectives. While the data presented in the review do not dig deep into green composite material sciences in detail, it is anticipated that the most suitable applications for green composites will be made better known to engineers and designers. It is expected to contribute to the growing use of green composites and eventually boost the quality of our material systems.

Conflict of Interest

The authors declare no conflict of interest.

Supporting Information

Not applicable.

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