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Review

Comprehensive review on plant fiber-reinforced polymeric biocomposites

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ABSTRACT

The expansion of environment-friendly materials based on natural sources increases dramatically in terms of biodegradable, recyclable, and environmental disputes throughout the world. Plant-based natural fiber, a high potential field of the reinforced polymer composite material, is considered as lightweight and economical products as they possess lower density, significant material characteristics, and extraordinary molding flexibility. The usage of plant fibers on the core structure of composite materials have drawn significant interest by the manufacturers to meet the increasing demand of the consumers for sustainable features with enhanced mechanical performances and functionalities. The plant fiber-based composites have widespread usage in construction, automotive, packaging, sports, biomedical, and defense sectors for their superior characteristics. Therefore, this critical review would demonstrate an overview regarding the background of natural fiber composites, factors influencing the composite properties, chemical interaction between the fiber and matrices, future potentiality, and marketing perspectives for triggering new research works in the field of biocomposite materials.

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Abbreviations

2D	Two-dimensional
3D	Three-dimensional
BCs	Biocomposite
C	Carbon
Ca^{2+}	Calcium ions
CH_4	Methane
ClO_2	Chlorine dioxide
CO_2	Carbon dioxide
COOH	Carboxyl
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimetry
EEE	Equity, Ecology, and Economy
FE	Finite element
FM	Flexural modulus
FS	Flexural strength
GPa	Gigapascal
$HClO_2$	Chlorous acid
HDPE	High-density polyethylene
IBS	Internal bonding strength
IROM	Inverse rules of the mixture
LCA	Lifecycle assessment
LCM	Liquid composite molding
MDI	Diphenylmethane diisocyanate
MOE	Modulus of elongation
MOR	Modulus of rupture
MPa	Megapascal
$NaClO_2$	Sodium chlorite
OH	Hydroxyl
PA11	Polyamide 11
PBAT	Poly(butylene adipate-co-terephthalate)
PCL	Polycaprolactone
PE	Polyethylene
PHA	Polyhydroxyalkanoates
PHBV	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate
PHU	Polyhydroxyurethane
PLA	Poly (lactic) acid
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
REV	Representative elementary volume
RIFT	Resin Infusion under Flexible Tooling
ROM	Rules of the mixture
RTM	Resin transfer molding
SCRIMP	Composites resin infusion manufacture process
SEM	Scanning electron microscope
SiC	Silicon carbide
TGA	Thermal gravimetric analysis
TM	Tensile modulus
TPS	Thermoplastic styrenic elastomers
TS	Tensile strength
VARTM	Vacuum-assisted resin transfer molding
XRD	X-ray diffraction

Introduction

Significant attention rose from environmental issues and safeguarding of natural assets for the development and designing of natural materials by using renewable raw materials, which has become an obligatory task for safe living. To replace the synthetic material-based composites, manufacturing industries have drawn considerable attention to plant fiber (hemp, flax, ramie, jute, sisal, kapok, kenaf, coir, rice husk, and so on) reinforcements as an alternative option [1–5]. These natural fibers are importantly using in the field of textiles for many years where flax was used approximately 7000 years before ancient Egypt. Archeologists have found and reported that even for the people of the Stone age, the technology for twisting short staple fibers to manufacture yarns and cords using a spinning method was not very much dissimilar from that applied in ancient regions of the world at that time [6–9]. However, the application of these fibers in composite materials has amplified over the last few decades for their relatively low-costs and environment-friendliness compared to the traditional artificial materials (aramid, glass, and carbon fibers), their recyclability, biodegradability, low density, lighter weight, required fiber aspect ratio, less abrasiveness, minimal health hazard issues and also decent thermal, electrical, and acoustic insulation properties and their relative strengths per unit weight of the material [10–13]. During the development of a new product, it is demonstrative to concern about EEE facts, i.e., Equity, Ecology, and Economy in terms of achieving a sustainable equilibrium that can fulfill the satisfaction [14–17]. In contrast, these synthetic fibers have serious demerits for their preliminary processing costs, machine abrasion, utility consumption, etc., whereas in some cases, it is still limited within laboratory boundary rather than industrial applications.

This review will report plant-based natural fibers as reinforcing materials, their elements in composites, their factors influencing the properties of the composite, and their response in chemical treatments as well.

The biological configuration and the anatomy of plant fibers are highly complex. Naturally originated plant fiber-based composite materials are termed as BCs. However, Reddy et al. defined the bioplastic in terms of different production routes: (a) renewable—BCs are derived or synthesized from various plant or animal-based renewable sources (cellulose, lignin, chitosan, protein, PLA (poly (lactic) acid), PHA (polyhydroxyalkanoates), and so on), (b) petroleum-based—although derived/synthesized from petroleum-based resources but still biodegradable after the end-uses of the products (PBAT (poly(butylene adipate-co-terephthalate)), PCL (polycaprolactone), and so on), (c) mixed sources—combinations of petroleum and bio-based monomers like bio-thermosets (such as bio-based epoxy and polyurethanes) and bio-based blends (such as polyester) [19–21]. They fundamentally contained a rigid and crystalline cellulosic microfibril reinforced amorphous (as shown in Fig. 1) structured lignin and hemicelluloses in the matrix. Generally, plant fibers are comprised of cellulose, lignin, hemicelluloses, oil, waxes, protein, and different water-soluble components, whereas cellulose, lignin, and hemicelluloses are the primary polymeric constituents. However, cellulose is the basic chemical composition of any plant-based natural fibers [22]. The chemical formula of cellulose (Fig. 2a) comprises of three (hydroxyl (–OH)) groups. Two of the –OH groups are capable to make hydrogen bonds in cellulose macromolecules, while the remaining –OH group makes a hydrogen bond with the other cellulosic molecules [23, 24]. Hemicellulose follows mostly in the primary cell wall and having branched polymers comprising five to six sugars of carbon (Fig. 2a) of diverse chemical assemblies. Lignin is a naturally originated amorphous polymer that possesses a well-oriented aromatic assembly (Fig. 2c) [25, 26]. Pectin consists of complex polysaccharides, whereas their side chains remain cross-linked with arabinose sugars and Ca^{2+} (calcium ions).

Furthermore, small quantities of inorganic (ash) and organic extractive components remain in the fiber assembly. Organic constituents are liable for coloration effect, smell generation, and resist the deterioration, while inorganic extractives increase the harsh properties of the fiber. The complete removal of non-cellulose substances from these fibers is the most challenging factor as it is expensive to do the pretreatment. A significant characteristic of natural fibers is their attitude to grasp the moisture from the air [22], as the cellulose is hydrophilic in nature. Generally, most of the polymeric fibers swell because of moisture absorption properties which subsequently lead to altering in material weights and physical size, even in both the longitudinal and torsional strengths as well as stiffness [28–30]. Furthermore, natural fiber is subjected to biological degradation (Fig. 3). A recent study by Summerscales e al. [31] has mentioned that the usage of organisms and associated enzymes could offer a promising degradation potentiality for developing sustainable composites which would minimize the necessity for conditioning of mildew reactions and energy consumptions from the ecosystem of the universe. This study has further reviewed the usage of enzyme and organisms especially for bast fibers and associated composites in terms of (a) extracting fibers from plants through the retting process, (b) modifying the fiber surfaces, and (c) treatment after end-use of the products [31]. In terms of durability, plant fibers are not decent as synthetic fibers. A wide range of micro-organisms

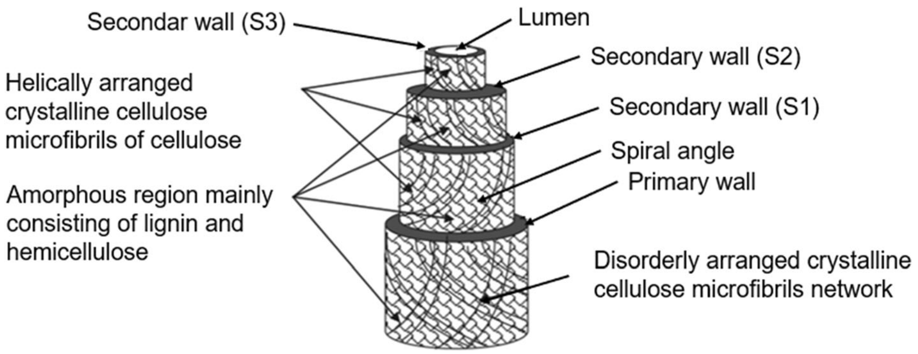


Figure 1 Representation of cellulosic fibers. Adapted with permission from Elsevier [18]. Copyright Elsevier, 2018.

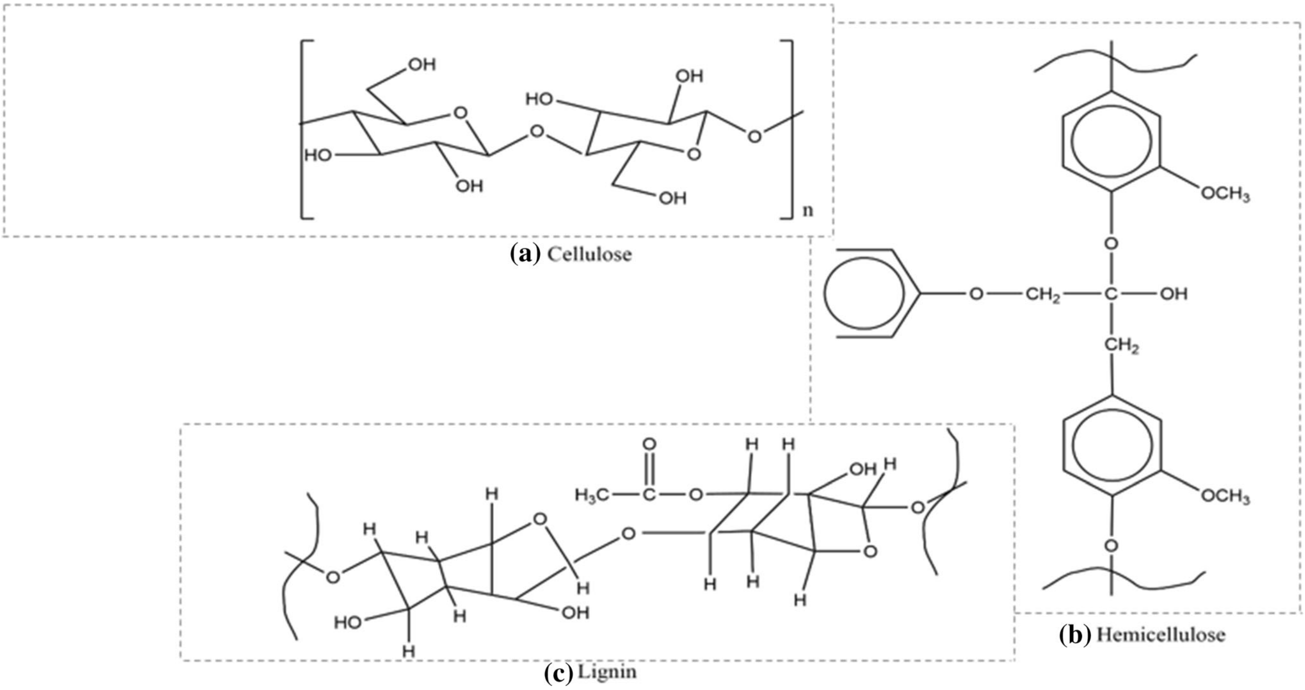


Figure 2 Chemical configuration of **a** cellulose, **b** hemicelluloses and **c** lignin. Adapted with permission from Elsevier [27]. Copyright Elsevier, 2020.

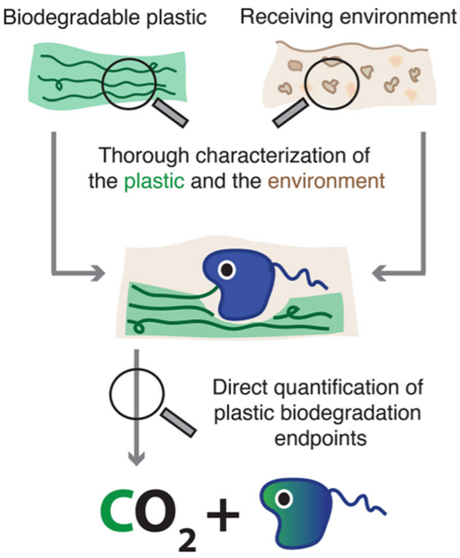


Figure 3 Biodegradation of plastic materials requires clear characterization of plastics and disposed environment. Reprinted with permission from ACS [37]. Copyright ACS, 2020.

can easily attract the plant fibers in the high humid environment, leading to rot and decomposition [32–35]. By the way, plant fibers are recognized as prominent biodegradable and renewable materials with the capability of carbon dioxide (CO_2) emission reduction [36]. Zumstein et al. [37] discussed some factors for biodegradable plastics over traditional non-biodegradable plastics, where the authors have mentioned that bioplastic should be investigated for two categories to confirm that they really could mitigate the plastic-based environmental problems. In the case of the first category, they have suggested that the plastic receiving environmental system (Fig. 3) should have the capability to metabolize the organic plastics through measuring the plastics carbon (C) conversions into methane (CH_4) or CO_2, quantitatively, whereas the second category entails that there should be rigorous information on certain incubation conditions like temperature, time, and relative humidity beside the specific properties of polymers [37].

Plant fibers are further classified according to their origins, i.e., whether they are collected from any parts of plants (such as flowers, stem, leaves, and husk). Conferring to the different research groups, plant fibers have prominent significance because they functioned as reinforcement material in plant fiber-reinforced composites. Plant fibers entail bast fibers (jute, hemp, flax, ramie, and kenaf), leaf fibers (banana, sisal, and pineapple), seed fibers (oil palm, milkweed, and cotton), fruit fibers (coir), cereal straw, grass fibers, root fibers, (*Cissus quadrangularis*), and wood fibers as shown in Fig. 4 [2, 38]. Besides some commonly used natural fibers recently, rice husk and reed-based natural fibers are also gaining attention for manufacturing BCs. Zareei et al. [39] has reported the benefits of using rice husk as composite materials. One of the most prominent findings from their research was that there was a 20% increase in compressive strengths found for 15% usage of rice husk [39].

Nanocellulose is also going to be a highly prominent research area for the current researchers for the development of nanocomposites [40]. Nanocellulose exists some convenient features like low-cost, biodegradability, lower density, lower energy consumptions, better surface reactivity compared to the macro- or micro-cellulose-based composites [41–43]. The feasibility of using nanocellulose is also showing extensive potentiality for applications in the automotive, biotechnology, electronics, and packaging industries. However, nanocellulose also possesses some critical disadvantages as well such as higher moisture absorption, incompatibility with the polymer matrix, limited temperature processability, and poor wetting characteristics for being applicable as feasible raw materials for BCs production [44, 45]. But, the researchers are continuously trying to develop some newer technologies and methods for overcoming the major limitation of nanocellulose-based composites [46–49].

However, there are also some limitations of using plant fibers as raw material to produce BCs such as the inconsistency of plant-based fiber is a big challenge that limits industrial-level manufacturing. The fiber quality depends on the harvesting season and parts of the plant that the fiber is collected which impacts the mechanical performances of the fibers [51, 52]. So, it is recommended to focus on some factors as illustrated in Fig. 5 before selecting the natural fibers or materials for producing BCs. Although there are enormous benefits for using bio-based fibers full replacement is still challenging because still now, not enough data are available regarding the utilization of BCs from different plant-based fibers. The natural fibers have poor durability against alkaline conditions along with a risk to be attacked by microbial agents and insects. Besides, the hydrophilic nature of plant fibers causes the swelling of water in BCs when contacted with the water

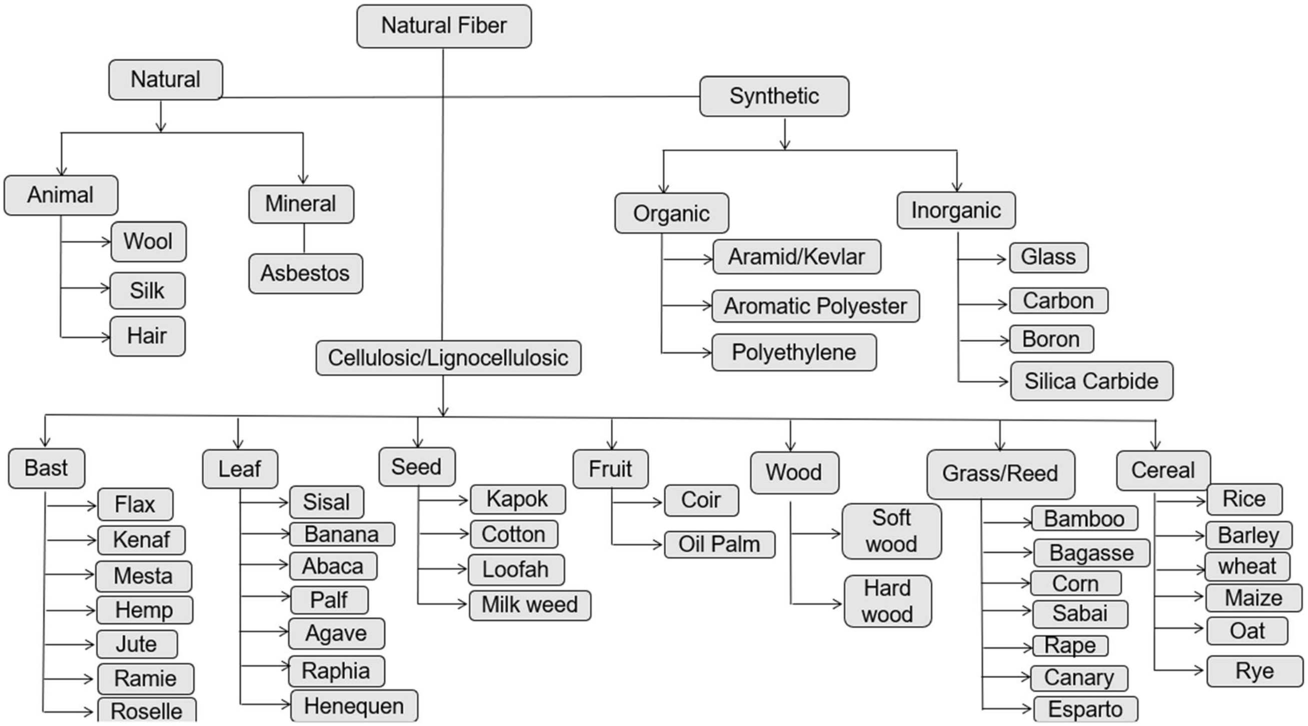


Figure 4 Natural fiber classification. Adapted with permission from Elsevier [50]. Copyright Elsevier, 2015.

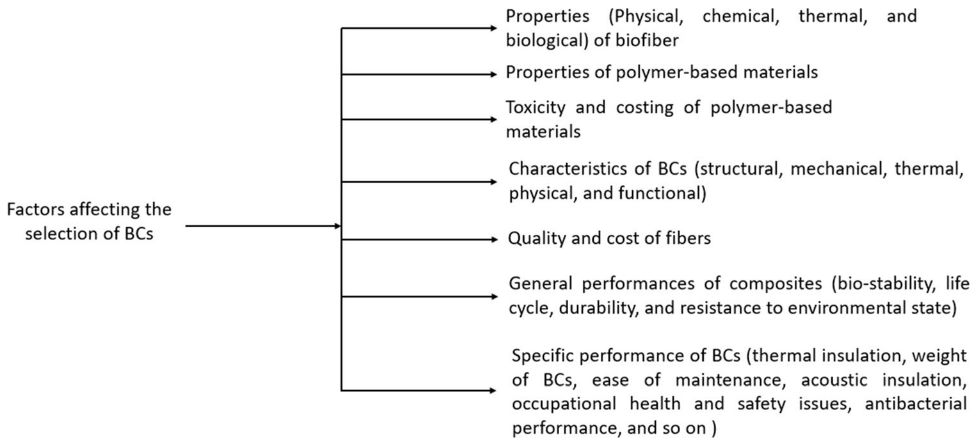


Figure 5 Influencing factors for biocomposites selection [51, 55].

[53, 54]. This critical review is stimulated toward highlighting the groundbreaking understanding of intellectuals on the reinforcement of plant fiber with some polymeric materials to open advanced areas of research for BCs in terms of academic and commercial use.

Elements of plant fiber composites

The application of plant-based natural fibers in BCs has drawn significant interest over the last several decades. These sorts of BCs offer a wide range of compensations over man-made fibers for a cheaper cost, low density, availability, biodegradability, as well as biocompatibility [56]. The most widely used plant fibers as shown in Fig. 6 for BC productions are bast fibers including jute [57], hemp [58], kenaf [59], flax [60–62], and sisal [63]. This is because of their sophisticated specific strengths compared to glass fiber and an equivalent specific modulus [64]. Due to these characteristics and availability of resources, these natural fibers hypothetically propose essential specific strengths, stiffness and modulus, at a competitive cost [65]. Although a lot of plant fibers can be used for producing composites experimentally, but most of them are still limited in the laboratory scales only because of low feasibility and research compatibility for industrial productions. Therefore, a limited number of fibers are found by agronomic processing, industrial, or through after end-use which have already been reused by automotive industries in Europe, and this technique has beyond the boundary of North America [66, 67].

The chemical constituents of plant fibers have been stated by different researchers [68]. The application of plant fiber-reinforced polymer composites has drawn great attention and interest among the scientists. The key research on cellulosic fibers carried out on properties such as chemical, mechanical, dielectric, and thermal properties in terms of X-ray diffraction (XRD), thermal gravimetric analysis (TGA), scanning electron microscope (SEM), differential scanning calorimetry (DSC), and dynamic mechanical analysis (DMA) which are capable to provide fundamental support for subsequent processing and practical applications [69–71]. Another important field of research is studying the interfacial characteristics between the matrix and cellulosic fiber [72, 73], where the fast and foremost aim is the modification of fiber surface by means of thermal and chemical treatments to intensify the bonding between fiber and matrix as well as reduction in water absorption by natural fibers [74, 75]. Thereafter, properties of natural fiber-reinforced polymer composites comprise thermoplastics (polypropylene (PP), polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC)), thermosets (polyester, epoxy, etc.), rubber (styrene-buta-diene rubber, natural rubber, etc.), cement, and gypsum [3, 76–78]. The impacts of processing technologies as well as composite parameters such as length, orientation, the volume fraction of fiber, and fiber-surface modification processes enhance the mechanical properties of BCs. The most significant advantage of using natural fiber-based composite is the low volume of carbon footprint and disposals to the environment (Fig. 7). BCs have been investigated along with numerous theoretical models to predict the properties of the composites [79–81]. Berk et al. [82] has presented a micromechanical model to predict the tensile strength and modulus of the BCs through providing inherent statistical variations from

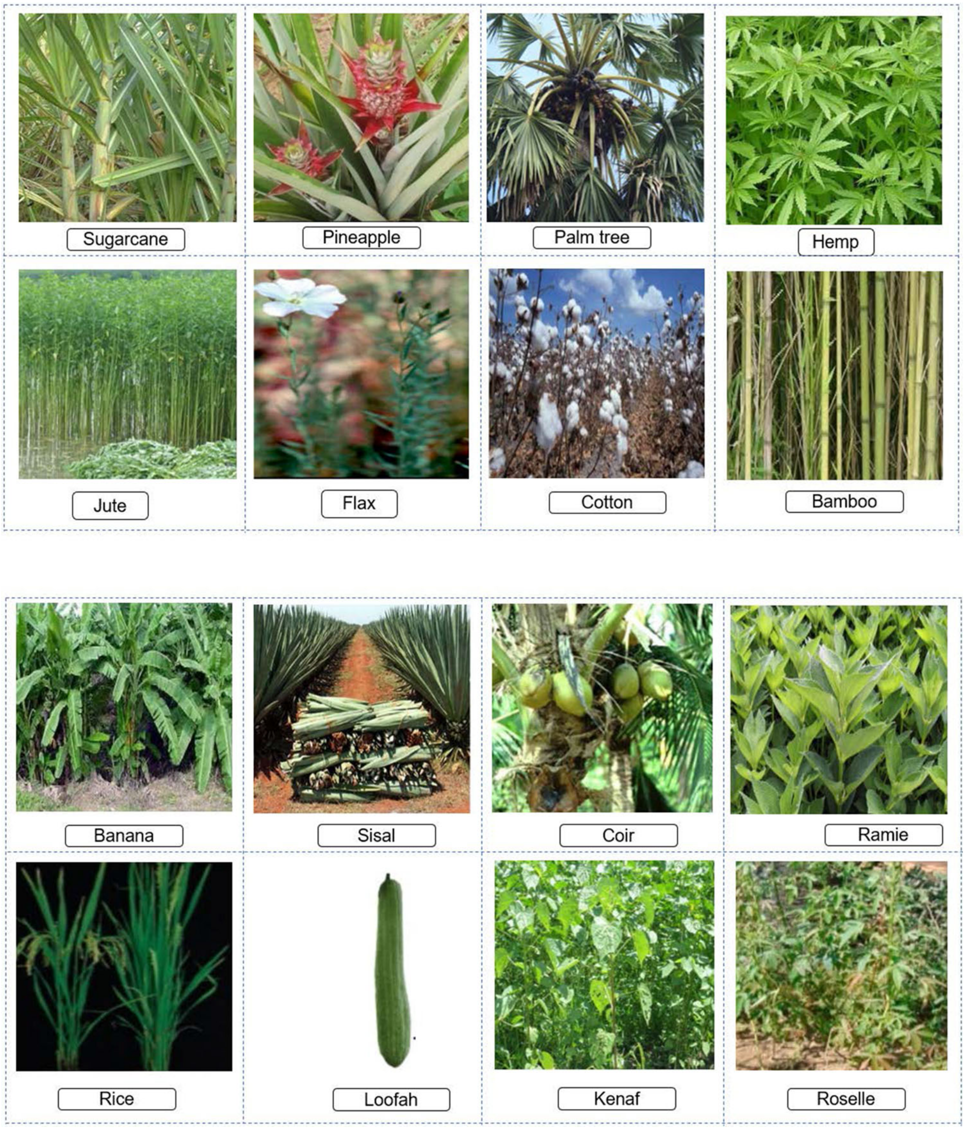


Figure 6 Natural fiber originated plants of sugarcane, pineapple, palm tree, hemp, jute, flax, cotton, bamboo, banana, sisal, coir, ramie, rice, loofah, kenaf, and roselle. Adapted with permission from Elsevier [83–87]. Copyright Elsevier 2011, 2016, 2018, 2019.

plant fiber reinforcements in polymeric composites. The same study has also predicted the tensile modulus and strengths first and then tested experimentally on jute/epoxy BCs and found satisfactory improvements on predictions.

Plant fiber-based composite ingredients are going to be considered as a prominent material for the convenient cost-effective features and industrial accessibility. However, natural fibers also exhibit a considerable range of inconsistent mechanical and physical properties which are depending on the topographical source, weather growth circumstances, and processing methods [88]. A series of researches have been carried out primarily in the field of plant fiber composites such as effects of water absorption in case of pultruded composites encompassing some low profile additives and fillers [89], mechanical properties analysis on cost competitiveness for different BCs such as jute-polyester composites [90]. However, according to some previous researches [89–92], the techniques of moisture diffusion involved three distinct mechanisms in the polymeric composites system. First of all, the water molecules diffuse inside the microspace between the polymer chains. Secondly, capillary transportation occurs into space and flaws which interfaces between the plant fiber and matrix. The third mechanism comprises the transport of microcracks in the matrix arising from the swelling of natural fibers (mostly in the case of plant fiber composites) [93]. So, these mechanisms suggest a classification of absorption behavior which includes: (i) linear Fickian behavior: moisture weight

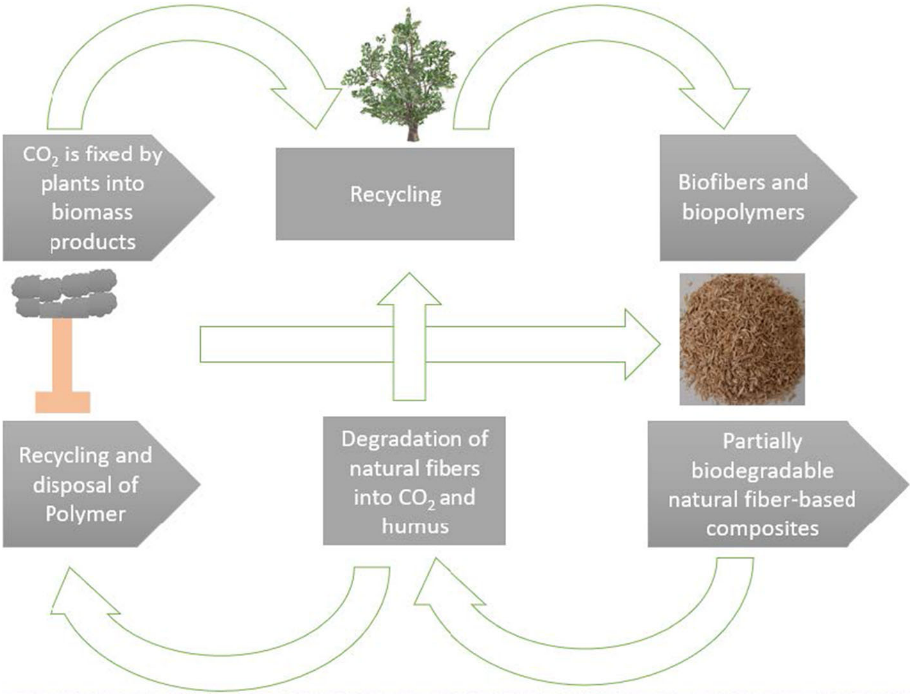


Figure 7 Circular economy impacts of natural fiber-reinforced composites.

Table 1 Comparative study between the thermosetting and thermoplastic polymers. Adapted with permission from Elsevier [97]. Copyright Elsevier 2012

Serial	Advantages	Disadvantages	Polymer type
(a)	The lower viscosity of the resin	Brittle	Thermoset
(b)	Good wetting of fiber	Not recyclable via standard procedure and method	Thermoset
(c)	Exhibit excellent stability against thermal treatment once polymerized	Not post-formable	Thermoset
(d)	Chemically resistant		Thermoset
(e)	Recyclable	Poor melt flow, Need to apply heat higher than the melting temperature for composites production	Thermoplastic
(f)	Easy to mend by solvent bonding and welding		Thermoplastic
(g)	Post formable		Thermoplastic
(h)	Tough		Thermoplastic

gains progressively and reaches a balanced condition after a quick primary take-off; (ii) pseudo-Fickian behavior: where moisture weight gains but never extended to a balanced condition after primary take off; (iii) double-phase diffusion technique: where a sudden rise in moisture contents gain after the initial take off; (iv) swift moisture gain consequences from matrix cracking and fiber/matrix debonding and; (v) moisture content gain trails a decreasing trend after initial take off, a permanent process as a consequence of the leaching out of material from the bulk following physical or chemical collapse [89]. The properties of different polymers (thermosetting and thermoplastic) also exist significant effects for the mechanical characteristics and performances of BCs [94]. Some of the major merits and demerits of these two polymers are provided in Table 1.

Polymer matrix

BCs are formed with plant-based fiber materials and the polymeric matrix. A matrix can be identified as a base material as well as binding material for BCs that is applied to grip the fibers in a particular place and capable of relocating additional forces to inner reinforcements. The phase of the matrix could be a polymer (originated from non-renewable or renewable sources) or a mineral binder such as ordinary Portland cement/gypsum. The bio-based polymers are PLA, thermoplastic styrenic elastomers (TPS), cellulose, polyhydroxyurethane (PHU), polyamide 11 (PA11), polyhydroxyalkanoates (PHA), PHBV (poly(3-hydroxybutyrate-co-3-hydroxyvalerate)), and so on, whereas synthetic polymers are PP, PE, and PVC. The polymers are further classified as thermoplastics and thermosets. Either thermosets (epoxies, polyurethane (PU), silicone, phenolics, and unsaturated polyesters) or thermoplastic matrices (PP, elastomers, and PE, PS, PVC, and polyamide) are extensively applied for BC formations especially for plant fiber reinforced polymeric composites [95, 96]. These matrices have a distinct chemical formula and able to express various reaction capabilities with fiber surface molecules when subjected to the composite formation. Although both the thermoset and thermoplastic matrices exhibit a wide range of benefits and hindrances, it is claimed that thermoset matrices exist good fiber wetting and lower resin viscosity properties, and outstanding thermal stability when polymerized and chemically functionalized, whereas thermoplastic matrices are easy to recycle, convenient to repair by solvent bonding and welding, post-formable as well as tough material formation. Some of the properties of thermoplastic and thermoset polymers are given in Table 1. But in contrast, thermosets are brittle and non-recyclable through standard methods and not post-formable. In comparison, thermoplastics demonstrate poor melt flow and require the heat above the melting point for processing purposes [95]. Characteristics (density, tensile strength, elastic modulus, and elongation) of various thermoplastic and thermosetting polymers are provided in Table 2.

Textile fabrics have also drawn the attention of BCs researchers for their convenient capabilities to be used as attractive structural materials. The outstanding mechanical characteristics of textile fabrics reinforced composites entail increased strength, transverse moduli, enhanced damage tolerance, and shear resistance, which has made them potential composite materials. Besides, the dimensional stability of fabric-based polymeric composites is significantly stable. The most commonly considered textile materials are researched by the scientists includes woven, non-woven, and knitted fabrics. Woven fabrics have taken place a significant position for composites productions [61, 62, 98]. The woven fabrics could be either two-dimensional (2D) or three-dimensional (3D) fabrics [99]. In the case of 2D woven fabrics, two types of yarns are used, whereas three sets of yarns are used for 3D woven fabrics. Herein, 2D fabrics provide better dimensional stability and better properties in orthogonal directions. The 3D fabrics have widespread applications for biomedical and aerospace applications for their feasible structural geometry, strength, and stiffness toward thickness directions [99, 100]. Tiber et al. [101] conducted a study on knit fabric reinforced composites and reported that knit fabrics made from bamboo/epoxy BCs provided higher fracture toughness and bending strength compared to viscose/epoxy and modal/epoxy composites. Kenned et al. [102] has reported

Table 2 Characteristics of different polymers used for composites production [103, 104]

Polymeric resin	Type of resin	Density (g/cm^3)	Elastic modulus (GPa)	Tensile strength (MPa)	Elongation (%)
PLA	Thermoplastic	–	0.35–3.5	21–60	2.5–6
HDPE	Thermoplastic	0.94–0.96	0.4–1.5	14.5–38	2–130
LDPE	Thermoplastic	0.910–0.925	0.055–0.38	40–78	90–800
Nylon 6	Thermoplastic	1.12–1.14	2.9	43–79	20–150
PS	Thermoplastic	1.06–10.4	4–5	25–69	1–1.25
PP	Thermoplastic	0.899–0.920	0.95–1.77	26–41.4	15–700
Starch	Thermoplastic	–	0.125–0.85	5–6	31–44
Epoxy	Thermoset	–	3–6	55–130	2–10
Polyester	Thermoset	–	2.07–4.41	41.4–89.6	2–2.6

about non-woven banana fiber reinforced PS (unsaturated) matrix which was fabricated using needle punched methods and found an enhanced flexural and tensile properties for 40 wt.% of fiber properties in contrast to 33 and 36% fiber content by the BCs.

Processing technique

In general, the basic processing principles of plant fiber reinforcements are comparable to those applied in handling synthetic fibers. The composition happened both in fabric or fibers form [105], for example, woven fabrics and direct use of short fibers, whereas they are either randomly oriented [106] or unidirectional (carded and fresh/raw) [107] based on fiber classification, staple length as well as orientation in thermoplastic and thermoset matrices. In the case of thermoset composite methods, the basic assembling technique is said as ''hand layup'', it means a manual blending system between the matrix and fiber. Where, achieving consistency (such as uniformity of thickness, the accuracy of fiber to matrix proportion, and avoiding void contamination) of the composite is a challenging task as sampling is entirely dependent on the skill of workforce. On the other hand, the resin is penetrated inside by means of vacuum pressure which is mixed with the fibers or fiber mats through vacuum-assisted resin transfer molding (VARTM) [108]. According to this technique, the resin penetration performance is significantly better in terms of minimum void contamination, precise fiber spacing, and the dimension of the composites than the hand layup method [109]. Francucci et al. conducted a study on natural jute fabric to investigate permeability on both saturated and unsaturated states, and they have found that the swelling and fluid absorption characteristics of natural fibers decrease the permeability [110]. The same study has further revealed that swelling of natural fiber happens for saturation; hence, the porosity is reduced and flow resistance is increased, whereas the flow velocity is decreased for unsaturated flow as the fluid is removed from the mainstream due to fluid absorption, while it travels over the reinforcements [110]. Moreover, Masoodi et al. [111] studied finite element (FE)-based modeling for simulating the flow of liquid-based resin polymers for investigating the swelling of natural fiber (jute) reinforced polymeric composites using liquid composite molding (LCM) methods. This study has found significant improvements in constant flow rate at constant injection pressure over traditional analytical approach in terms of permeability [111]. Furthermore, Nguyen et al. [112, 113] mentioned that LCM methods have the higher potentiality to produce BCs with higher fiber volume fractions through enhancing mechanical properties at comparatively lower temperature through reducing the risk of fiber degradations. They have further claimed that natural fibers diameter and porosity play a significant role in inconsistent results and two different liquids provide different fiber permeability [112]. In the case of a thermoplastic matrix, there are two efficient techniques: compression and injection molding. Mixing of fiber/fiber mats is passing through a series of heated roller/plate and pressed them under an absolute pressure in compression molding technique. In contrast, for injection molding, the fiber–resin is loaded as granulate form into the machine, which is then melted into fluid form and finally injected through using high pressure [114]. The interactions between fiber and matrix is performed by applying pressure (5 MPa) and temperature (over 200 °C), depending on the melting temperature of matrix. Another popular technique applied for both types of thermoplastics and thermosets is the composite pultruded profile, which is fabricated through pulling the reinforcement by a heated die which is finally mixed with the matrix [115, 116].

Bio-based composite manufacturing methods

BCs are getting public concerns in terms of competitive alternative of traditional synthetic fiber like glass/carbon fiber-reinforced composites. However, although natural fiber composites are booming recently, the fabrication could still be similar to glass fiber in most cases [117]. The well-known fabrication methods for BCs are hand lay-up, compression molding, RTM (resin transfer molding), VARTM, extrusion, and injection molding.

Hand lay-up

Hand lay-up is a simple and old open mold technology used for the fabrication of BCs. This method is suited for large components as it is a low-volume and labor-intensive technique [119]. Natural fibers/

woven and non-woven fabrics/ other reinforcements are manually positioned/placed into the mold, where the polymeric resin/matrix is poured and sprayed/ brushed over the laminations. Initially, the mold is placed over the Teflon paper (coated with resin releasing agent like wax). The entrapped air inside the laminated matrix is removed by using squeeze rollers over the laminates. After the resin spraying, another Teflon paper is positioned over the laminated composites and put under environmental conditions for a certain period of time like 24 h to ensure curing. The thermoplastic polymers like epoxy/polyester/ MDI (diphenylmethane diisocyanate) resins are widely used for hand lay-up methods [119–121].

Injection molding

Injection molding is used for mass composites production by the manufacturers. The materials are injected into the mold to produce BCs in the case of an injection molding machine (Fig. 8b). Injection molding could be performed for both types of thermosetting and thermoplastic polymers. The polymeric materials (pellets/granules) are fed into a heated barrel, which is then mixed and forced to a mold cavity for cooling and hardening according to the cavity configurations [122]. Injection molding machines are available in different types of configurations either horizontal or vertical. Besides the configurations, every injection molding machine's power source, mold assembly, clamping, and injection units for performing operation cycles are smooth. The main functioning of the injection unit is to heat and inject the materials into the cavity mold.

Compression molding

Compression molding an old and mass scale lighter weight thermoplastic composites production method. The mold materials are placed in the open space of the mold cavity (preheated). The mold is then closed, and pressure is applied as if the molded materials get uniform contact throughout the entire BC area constantly until the curing. Compression molding is a simple and discontinuous method just to place a mold between the metallic plates of a hydraulic press device (Fig. 8a). The polymeric materials are molted by applying heat with constant pressures on the mold to fill the mold. Conversely, the thermoplastic materials are needed to be cooled upon applied pressure before ejecting from the machine. But the cooling step is not mandatory for thermoset polymers as they are solidifying under processing pressures for stronger crosslinking. The most important parameters to

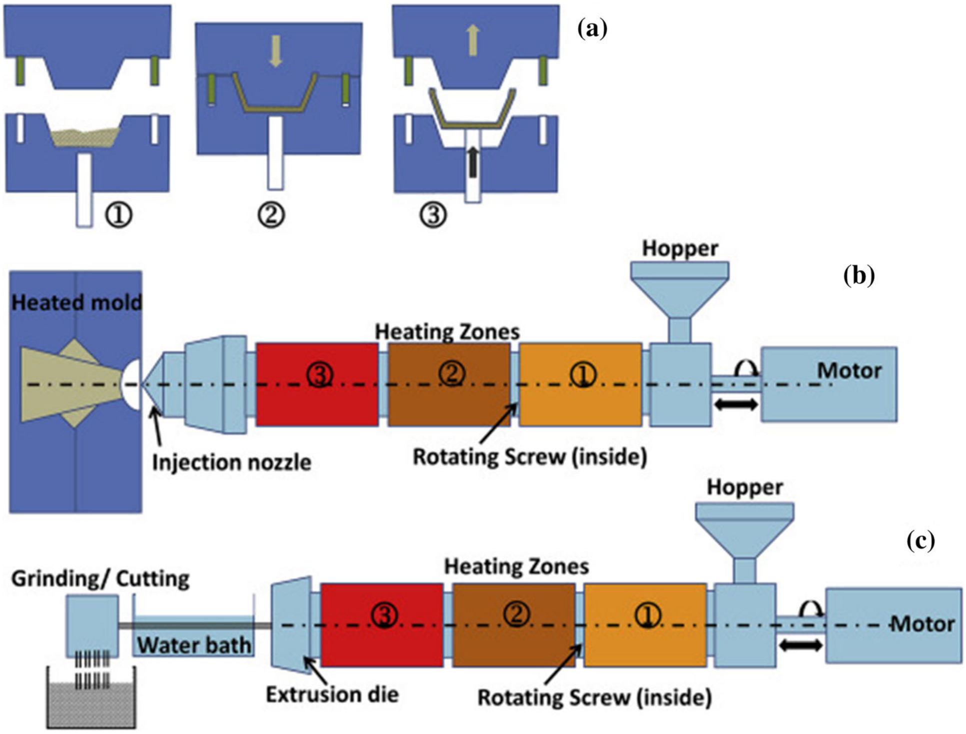


Figure 8 Schematic drawing of **a** compression molding, **b** injection molding and **c** extrusion molding of plant fiber-reinforced composites. Reprinted with permission from Elsevier [118]. Copyright Elsevier, 2019.

maintain during the operations are BC density, thickness, dimensions, time (both heating and cooling), temperature, and pressure [123].

RTM molding

In the case of resin transfer molding (RTM) molding, the reinforcement material (woven fabric/mats) is positioned by hand into a mold and the mixture of resin is injected into the mold cavity. In the beginning, the reinforcement fibers are positioned into a mold set, which is clamped and closed. Later the polymeric resin is applied to the mold cavity using pressure. Generally, the atmospheric pressure is lower than the mold cavity pressure. However, this phenomenon is opposite for the vacuum infusion technique where the atmospheric pressure is higher than the mold cavity pressure. The fibers get swell for vacuum infusions under a certain period of time during the RTM process [110, 124]. The RTM technology is used for low molding pressure or when there is a necessity for the two smooth surfaces [125]. Finally, the composite is cured by applying certain pressure and heat.

Vacuum infusion process (VARTM/SCRIMP/RIFT)

The dry fiber materials impregnation has become a preferable composite manufacturing method, especially for larger materials. In this regard, a trend on further development or modifications of existing techniques has made different acronyms [126]. Willian et al. [127] reported the historical development of infusion processes, where they have used RIFT (Resin Infusion under Flexible Tooling) as collective processing terms. RIFT was categorized under four types (I–XIV) by Summerscales et al. [128], where type I is associated with "in-plane flow," type II for "through-plane flow," type III for "resin film infusion," and type XIV for "Semipreg" [126, 129]. However, different acronyms are sometimes confusing as Summerscales stated VARTM as "type I RIFT," whereas another study [130] has revealed VARTM as "type II RIFT." The term VARTM is used for different processes, which interpretation differs from country to country [126]. A modification was carried out on the VARTM technique, termed as SCRIMP (Seemans Composite Resins Molding Process) also based on "type II RIFT." This approach is suitable for the swift distribution of resins on the materials. The knitted or woven textile fabrics tend to resist the resin flow little lower; hence, SCRIM method ensures planer and swift distribution of resins [126]. Dewan et al. performed a study on VARTM-assisted jute/polyester fabric reinforced nanocomposites [131].

Factors influencing the BC properties

Structure of cellulose

In order to get an in-depth understanding of plant fiber-reinforced composites, it is necessary to know about the basic polymer system of naturally originated fibers which are mainly cellulosic in structure other than some protein fibers such as silk and wool. It is also pertinent to argue what is acknowledged about their physical and structural constituents, which will be restricted to cellulose, hemicellulose, lignin, waxes, and pectin. However, the word "cellulose" was initially introduced by Anselme Payen [132] in 1838, through his proposal about a purification method of plant tissue, linters of cotton, pit, root tips, and ovules from flowers of the plants by means of acid-ammonia treatment methods, which was then extracted in water that formed a constant fibrous substance. According to this proposal, it has commonly been recognized that cellulose is nothing but a linear polymeric structure containing D-anhydroglucose units connected by beta-1,4-glycosidic linkages. The arrangement of anhydroglucose units are not parallel perfectly in the plane but supposed to be a chair conformation, with consecutive glucose extractives rotated via an angle of 180° with respect to their molecular axis [133].

Structure of plant fiber

The basic structure of plant fiber is cellulose which is comprised of amorphous and crystalline regions. The crystalline area contains a significant number of bonds termed as strong intramolecular hydrogen bonds which are capable of creating the cellulosic block, enhance difficulties for other chemical entrances. However, the fiber treating chemicals such as dyes, pigment, or any other polymeric fillers are taking position gently into the amorphous region of the fiber polymer system. The –OH groups that are hydrophilic in nature exist in these (amorphous) zones are connected with atmospheric water molecules. These water molecules are generally held by lignin, hemicellulose, waxy substances, and pectin. This ensures the fiber hydrophobicity and polarity, which reduce the compatibility with hydrophobic or non-polar matrix [23, 134, 135]. Furthermore, natural fibers are subjected to a series of chemical modifications for the swelling of the crystalline area as well as the removal of the hydrophilic –OH groups and the elimination of surface contaminations such as waxy ingredients. Chemical operations such as scouring, bleaching, mercerizing, peroxide, benzoylation, coupling agents, and acetylation by means of heat or without applying heat are extensively employed for the modification of fiber surface and fiber polymer structure [118, 136–139].

Thermal properties of fibers

Usually, in the case of lignocellulosic fibers, degradation happens at about 240 °C temperature. However, polymer components of the fibers such as cellulose, lignin, and hemicelluloses are individually sensitive through various temperature ranges. The degradation temperature of lignin is more or less than 200 °C, whereas cellulose and hemicelluloses start the degradation at higher temperatures than lignin [95, 140, 141]. So, it could be an effective technique to enhance the thermal stability of the fibers by eliminating a significant amount of lignin constituents employing distinct chemical operations. Thermal response as well as degradation behavior of natural fibers is an immediate concern in the advancement of BCs manufacturing, more specifically extrusion, curing, or injection molding, even materials in amenity [25, 142].

Mechanical characteristics of plant fiber

A series of different factors (fiber length, filling, and alignment in the polymer matrix) have a fanatic influence on the mechanical properties of the BCs. When a certain amount of stress is applied to the matrix, the load is then dispersed along with the fibers vertical and horizontal axis uniformly. The load-bearing capacity widely depends on the aspect ratio of fiber length, the direction of applied load and molecular orientation of fibers, and finally, the harmonization amid fiber-matrix interfaces [143–145]. Three possible types of BCs can be designed according to the fiber coordination at the matrix. First of all, for higher tensile strength where fibers are longitudinally oriented in the BCs, but they mostly have minor compressive strengths due to fiber buckling. Second of all, for insufficient tensile strength where fibers are diagonally aligned, even where strength is less than the matrix strength. At last, for multiple mechanical properties, where fibers (basically short in length) are in the haphazard direction. Mechanical characteristics of different

Table 3 Mechanical characteristics of plant fibers

Plant fibers	Density (g/cm^3)	Youngs modulus (GPa)	Tensile strength (MPa)	Elongation (%)	References
Sugarcane	1.25	17	290	–	[83, 149]
Pineapple	0.8–1.6	1.44	400–627	14.5	[149]
Abaca	1.5	12	430–760	3–10	[83, 149]
Hemp	1.48	70	690	1.6	[83, 150]
Jute	1.3	26.5	393–773	1.5–1.8	[151]
Flax	1.4–1.5	27.6–103	343–2000	1.2–3.3	[151]
Cotton	1.5–1.6	5.5–12.6	287–597	7–8	[83]
Bamboo	0.6–1.1	11–17	140–230	–	[149]
Sisal	1.33–1.5	9–38	363–700	2–7	[151]
Coir	1.15	4–6	131–175	15–40	[150]
Ramie	1.0–1.5	24.5–128	400–1000	1.4–4.0	[151]
Kenaf	1.4	53	930	1.5	[83, 149]
Roselle	0.75–0.8	2.76	147–184	5–8	[152]
Banana	0.75–0.95	17.85	600	–	[152, 153]
Palm	–	2.75	377	–	[153]
Henequen	1.2	10.1–16.3	430–570	3.7–5.9	[151]

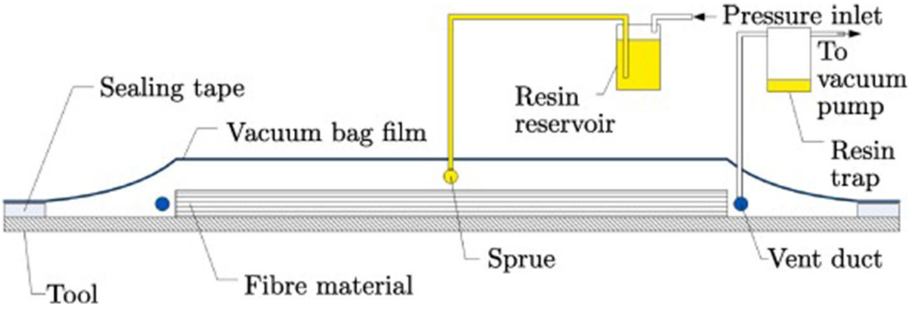


Figure 9 Schematic representation of VARTM process. Reprinted with permission from Elsevier [126]. Copyright, Elsevier 2019.

Table 4 Moisture content of several fibers at 21 °C temperature and 65% relative humidity [160, 161]

Natural fibers	Sisal	Coir	Flax	Abaca	Pineapple	Bamboo	Hemp	Ramie	Wood
Moisture content (%)	11	10	7	15	13	8.9	9	9	12

plant fibers have been provided in Table 3 for a better understanding of the mechanical properties of natural fibers to design the required BCs. For enhancing reliable mechanical characteristics, these haphazard orientations lead to the complications of load distribution at different routes and directions of these composites. By changing features, as for example, the aspect ratio, the diffusion, and alignment of fibers, it is possible to design through further improvement in the desired properties [118, 146–148].

Presence of voids

Air or different volatile substances possibly entrapped inside the BCs during the filling of fiber into the matrix. These voids are turned into micro-voids laterally in the distinct fiber tows and rich areas of the matrix after curing operation. This phenomenon results in a sudden breakage of BCs and subsequently reduces the mechanical characteristics [154, 155]. Another cause has also been claimed for void formation is curing, and the cooling rate of BCs [156]. A significant number of void content (more than 20% in terms of volume) is liable for secondary fatigue preventions, a higher tendency toward water diffusion, and a rise in scattered deviation of mechanical characteristics [157]. Even increasing the ratio of fiber content to base polymer in the matrix composites is proportionally increasing the chance for void formation (Fig. 9).

Water and moisture absorption of fibers

The cellulosic fibers that are containing lignin are mostly hydrophilic in nature and capable of absorbing moisture (Table 4). A significant number of hydroxyls (–OH) groups exist in the macromolecules of fiber cell walls are further subjected to breakdown and formation of a newer hydrogen bond with the water molecules when atmospheric moisture comes in contact with the fiber. The primary entrance of water molecules saturation occurs toward the cross section of plant fiber. The main reason for fiber swelling within the matrix is the result of the collaboration between hydrophilic fiber and hydrophobic matrix. This consequence is responsible to fade the strength of bonding at the fiber interface, which results in a subsequent impact on dimensional uncertainty, matrix's crack-down, and losing mechanical characteristics of the BCs [158]. Consequently, the elimination of moisture from fibers is a crucial phase for subsequent processing of BCs. So, prevention of moisture absorption from fibers is the preliminary challenge which can be decreased by inactivating hydrophilic groups (–OH) from the plant fiber polymer structure by means of a series of chemical treatments [159].

Chemical interaction between fiber and composite materials

The diffusion zone is also known as the reaction field is considered as fiber–matrix interface where two phases are merged either by chemical interaction and/or by mechanical bonding. This area plays a fundamental role to enhance the mechanical characteristics of the BC as its poor adhesion between two phases' boundary results in relatively weak dispersion of force as well as unsophisticated mechanical properties [159]. But the major challenge is the opposite nature of the fiber (hydrophilic) and matrix (hydrophobic) which consequences weak bonding at the interface. Thereafter, chemical treatments become an obligatory option for reinforcing fiber to reduce the matrix's hydrophilic tendency and thus improves compatibility [162, 163], whereas an alkaline treatment is widely applied for modifying the molecular structure of cellulose and densely packed crystalline structure of cellulose for forming an amorphous area which will ensure the proper penetration of chemicals [164, 165]. Alkali treatment of natural fiber is another common approach for the modification of the molecular structures of cellulose. This treatment is performed in aqueous solutions of NaOH. The –OH group is broken during this treatment and makes the reaction with water molecules (H-OH) to form alkoxide through leaving ionized reactive groups, as shown in Eq. (1).

$$\mathrm{Cell-OH+NaOH \rightarrow Cell-O-Na+H2O+impurity} \tag{1}$$

Silane is using for long times as a commercial coupling agent for modifying the surface of plant fibers too. The composition of silane is applied as a coupling agent to create a chemical connection between the matrix and fiber surface through siloxane bridge by means of few hydrolysis steps, the formation of bonds, and condensation [165, 166]. The reactivity of silane as shown in Eq. (2) is dependent on pH, temperature, organofunctionality, and the time for hydrolysis.

$$\mathrm{Cell-OH+R-Si(OH)_3 \rightarrow Cell-O-Si(OH)_2-R} \tag{2}$$

Esterification, as well as acetylation treatments, are mainly applied for plasticizing of natural fibers as shown in Eq. (3) where hydrophilic –OH groups of the natural fiber reacts with an acetyl group (CH_3-CO). They release out the existed moisture, which subsequently contributes to reducing the hydrophilic characteristics of plant fiber, thus enhancing better stability toward the dimension of the BCs [165, 166].

$$\mathrm{Cell-OH+CH_3-C(=O)-O-C(=O)-CH_3 \rightarrow Cell-O-COCH_3+CH_3COOH} \tag{3}$$

Sodium chlorite ($NaClO_2$) is applied as a bleaching agent for fiber treatment with an acid solution that is capable of acidifying and liberating $HClO_2$ (chlorous acid) through the oxidation reaction process and formation of ClO_2 (chlorine dioxide). This ClO_2 performs the reaction with lignin of plant fibers to remove it and also reacts with –OH groups of the hemicelluloses. This resultant phenomenon influences the elimination of moisture from the plant fiber in order to bring the hydrophobic nature of fibers [165, 167]. To enhance a significant interface property of fiber and matrix, peroxide treatment can be applied where peroxide initiates free radicals and react with –OH group of the natural fiber and polymer matrix.

$$\mathrm{Cell-O-Na+C_6H_5-COCL \rightarrow Cell-O-CO-C_6H_5+NaCl} \tag{4}$$

The treatment of peroxide could also enhance the interface property of natural plant-based fiber composites. Peroxide exist O–O bond in their ROOR functional groups. Some organic peroxides (for example, dicumyl peroxide and benzoyl peroxide) are widely used for cellulosic fibers surface modification that is highly reactive and acts for decomposing the free radicals (RO$^{\cdot}$). This is, in turn, incorporated with the macromolecular polymeric chain of cellulose through the reaction between the matrix and the –OH group of the plant fibers [165]. The reaction mechanism is shown in Eq. (5).

$$\begin{aligned}&\mathrm{RO-OR \rightarrow 2RO.,\ RO.+Polymer \rightarrow ROH+Polymer}\\&\mathrm{RO^{\cdot} + Celluose \rightarrow ROH + Cellulose^{\cdot}}\\&\mathrm{Polymer^{\cdot} + Cellulose^{\cdot} \rightarrow Polymer\ \text{-}\ Cellulose}\end{aligned} \tag{5}$$

Durability of BCs

The BCs provide a decrease in durability which consequences a decline and variation in mechanical strength and a challenge for bacterial and fungus attacks [181]. The natural fibers degrade in different weathering, humidity, hygrothermal, moisture, and so on conditioning which also affects the BCs durability. In this regard, the scientists are trying to investigate principal durability-related issues like moisture absorption, water resistance, thickness swelling, weathering, and so on [164, 182–184]. As natural fibers possess –OH group in their polymeric structure, they are hydrophilic in nature and absorb moisture [62] from the surrounding environment. This phenomenon of plant fibers has made it difficult to apply for outdoor applications. The cellulosic fibers swell upon absorbing moisture, which reduces the interfacial adhesions between the plant fibers and polymeric matrix [64] thus dimensional stability are hampered and failure of matrix happened [158, 185]. However, the moisture content and water absorption depend on the amount of biofiber loading, their orientation in the matrix system, relative humidity, temperature, void content, permeability, and so on. The surface modification and utilization of most suitable additives along with polymeric matrix could improve incompatibility [3].

Studies on creep

Creep indicates the increased deformations of materials gradually when it is exposed to long-term stresses. BCs upon extended applied stress consequences a decline in tensile strength and associated modulus [186]. The failure of BCs for creep results in cracking of composite structure, fracture of natural fibers, the yield of the matrix, pull-out of natural fibers, and interfacial debonding. A typical curve for creep could entail three stages, (a) primary creep, (b) secondary creep, and (c) tertiary creeps [187]. The stages of creep behavior are further shown in Fig. 10. The rupture of BC materials happened at the tertiary level of the curve. However, the creep behavior of the BCs could vary with the type of natural fibers, different materials, levels of stress (applied), temperature, relative humidity, and time exposure [187, 188]. Du et al.[187] has suggested that relative humidity possesses a significant influence on BCs creep; whether the humidity is increased from 20–50% to 65%, they have found a significant acceleration in creep strains. Xu et al. [189] claimed that higher temperature for the same loading of bagasse fiber with different matrix (PVC/HDPE) has made an increase in creep rate and instantaneous deformations.

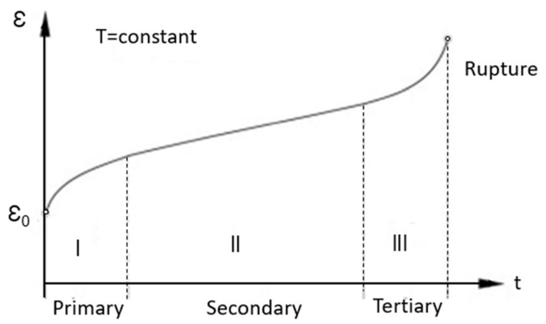


Figure 10 A stress–strain curve for creep testingure adapted with permission from Elsevier [187]. Copyright Elsevier, 2013.

Studies on fatigue

Fatigue expresses the catastrophic failure of BC materials upon fluctuating and dynamic loads for an extended period. The propagation and initiation of cracks are key causes for materials failure. This phenomenon is applicable when dealing with the failure related to fatigue. The fatigue behavior of BC materials is mainly led by the ductility of polymeric matrix and modulus of reinforced natural fibers [190]. The cracking of matrix, weaker interface, delaminations, fiber breakage, ply cracking (transverse), etc., are some of the key indicators for overall damage of BC materials [190]. The interface of natural fiber and matrix determines the mechanical properties of BCs. The transfer of stress at the interplay plays a vital role in assessing the failures mechanism associated with fatigue. As fatigue occurs throughout the entire BC materials, the fatigue stresses are complied with applied stress, torsions, and compression individually or sometimes combined with each other. However, fatigue stresses are normally conducted for ensuring the endurance limit/fatigue and lifetime of the BC materials under applied stresses [153, 160, 191, 192].

Tribological behavior

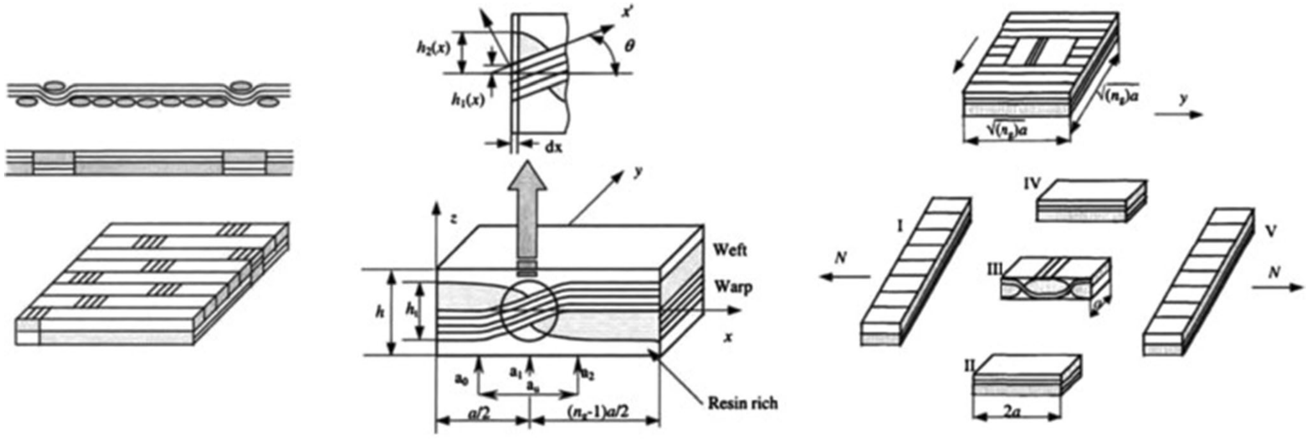
Tribological conditioning of the materials plays an important part in the failure of BCs, so the importance of modification on frictional and wear resistance properties of BCs could be understood. The researchers are trying to investigate and find out potential combinations for wear and frictional testing. The modified BC materials having superior wear behavior could easily be applied. The standard adopted for frictional and wear resistance properties of composite testing is ASTM G99-95a (2000) [193]. The testing of wear resistance properties is very sensitive as there is a deviation happened between the applied load (normal) and sliding speed of the composite materials, hence SiC (silicon carbide) is used to overcome such problems [190]. Bajpai et al. [194] has reported that the incorporation of PLA matrix on natural fiber-reinforced composites has significantly improved the wear characteristics upon different parameters (applied load 10–30 N, sliding speed 1–3 m/s, and distance 1000–3000 m) with 10–40% decrease in friction coefficient and 70% or more decline in wear rate from developed BCs.

Moisture durability

The polymeric composites especially the BCs could absorb moisture from the humid environment or when comes in contact with water [195, 196], which in turn consequences an inefficient poor stress transfer toward the interface of natural fiber–matrix. Moisture absorption of biofibers has direct effects on the thermal, mechanical, and physical properties of the produced BCs [93]. The BCs typically absorb 18–22% moisture after several months, 1–5% after a week, and 0.2–7% after a day (24 h) depending on the plant fibers chemical structures and properties, reported by previous studies [197]. The swelling of plant fibers in wet conditions could make accelerate the failure of BCs [198]. The moisture content of natural fibers has a significant influence on crystallinity, porosity and swelling of fibers, and tensile strengths. Conversely, the higher moisture content also enhances the risk of bacterial attack which expediates the biodegradations of the BCs. It is also investigated by the researchers that the loading of natural fibers could enhance the moisture absorptions which would negatively influence the properties of the matrix. Silva et al. mentioned that shrinkage of sisal fiber reinforced cementitious materials is influenced by the increased fiber volume [199]. The poor interfacial adhesion between the natural fibers and matrix enhances the chances of void creations around fiber, which consequences the higher water uptake. But, surface treatment of natural fibers could facilitate to overcome this challenge of voids along with achieving desired performances.

Resistance to fire

Flame retardancy is one of the most critical drawbacks of natural fiber-reinforced composites especially for the application areas like automobiles where higher safety and inflammability are considered. This is a crucial drawback for BCs, where the raw materials are derived from bio-based materials in contrast to synthetic fibers reinforced hybrid composites. The higher content of cellulosic polymers in



(a) (b) (c)

Figure 11 Schematic modeling of textile composites: **a** mosaic, **b** undulation, **c** bridgingure Reprinted with permission from Elsevier [203]. Copyright Elsevier, 2013.

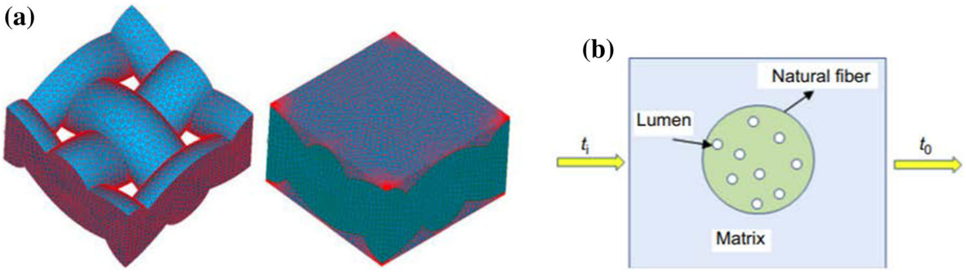


Figure 12 **a** Flax/epoxy BCs FE modeling, and **b** 2D modeling of natural fiber/polymeric resin. Reprinted with permission from Elsevier [205, 206]. Copyright Elsevier, 2016a, 2019b.

natural fibers and associated BCs increases flammability. It is found that cellulosic contents of plant fibers start to decompose within 260–350 °C temperature, whereas hemicellulose at 200–260 °C temperatures with generating less combustible gas in contrast to the cellulose [181]. Conversely, decomposition of lignin started from 160 °C which is further continued up to 400 °C. However, lignin generates more char compared to hemicellulose and lignin polymers. Another investigation has found that jute and flax contain nearly the same lignin content%; hence, their decomposition also follows similar degradation trends [200]. The variation in chemical compositions of plant fibers is responsible for variable flame retardancy properties in BCs. However, the plant fibers entailing higher lignin with low crystallinity provides higher resistance against fire. But, still, now, not so many researchers are interested in the fire resistance performance of BCs like mechanical properties. It is imperative to conduct the research for fire retardancy together the mechanical properties of developed BCs.

Numerical simulation and analytical modeling of BCs

Researchers and manufacturers nowadays are becoming more interested in predicting the mechanical performances in advance by using different numerical and mathematical modeling of the potential composite materials before going to operations. The main reason behind this motivation toward the modeling of composites is to comprehend the behavior of BCs in terms of the compositing materials characteristics [201]. Some of the most popularly used models are (a) Halpin–Tsai, (b) ROM (rules of the mixture), and (c) IROM (inverse ROM), whereas some less popular techniques are Christensen equation, bridging model, chamis model, and hashin and Rosen models [201]. Tian et al. [202] developed a nonlinear constitutive model for BC in terms of elastic response along with the aging temperature of the natural fibers and found that the theoretical results are comparable and demonstratable with the experimental results. The analytical modeling of BC materials developed by the researchers has received significant attention for the prediction of mechanical properties. This type of model is considered as a less complex and less time-consuming method for integrated optimized operation [203]. Analytical modeling depends on two main factors to determine the stiffness matrix: (a) homogenization method and (b) geometric modeling. The geometrical modeling enhances the necessity of components in terms of homogenization techniques. Besides, the geometrical modeling provides the fractions of fiber volume in representative elementary volume (REV) of the reinforcement materials. Different analytical models for textile composites are shown in Fig. 11.

FE analysis is used widely for modeling the natural fiber-reinforced composites. FE analysis is applicable to predict the micromechanical properties like strength, failure, and deformations, thermal properties like thermal conductivity, deformation of macroshape like a fracture and stress–strain [204]. REV is a popularly used method for modeling the influences of microstructures on the thermal and mechanical properties of BCs. The microstructure of plant fiber is complex and varies from plants to plants, especially their growing conditions like weather and the place of growth. Although it is challenging to predict the microstructure characteristics of plant fibers and their effects on associated BCs, FE has successfully made it possible especially for the effects on the type of reinforcement, orientation, the volume fraction of

Table 5 Origin and versatile potential applications of different natural fiber-based composites

Natural fiber	Origin	Application of BCs	References
Ramie	Stem	Fishing nets, filter clothes, furniture upholstery	[168, 169]
Flax	Stem	Window panels, fencing, bicycles, railing system, door shutter, and tennis racket	[170]
Hemp	Stem	Construction panels, geotextiles, furniture, and packaging	[169]
Sisal	Leaves	Doors, panels, and roofing sheets of construction industries	
Cotton	Cotton balls	Cords, goods, furniture manufacturing company	[169]
Kenaf	Stem	Mobile case, insulation, packing materials, bags	[169]
Coir	Fruit	Roofing sheets, building panels, packing, paper weight, mirror casing, brushes, mats, seat cushion, helmets, projector cover, and storage tank	[171]
Jute	Stem	Chip boards, door panels, building panels, roofing sheets, cords, sacks, geotextiles, I-shaped beams, water pipes, floor tiles, and transport materials	[171]
Rice husk	Fruit/grain	Bricks, building panels, decking, fencing	[168, 172]
Wood	Stem	Window frames, building panels	[168]
Bagasse	Stem	Windows panel, decking, fencing	[168, 172]
Abaca	Leaf	Road transportation, underfloor cover, tire well cover, and shipbuilding	[173, 174]
Bamboo	Stem	Window framing, fencing, automotive, aerospace, structural beam, and decking	[175–177]
Kapok	Fruits	Upholstery, pillow, toys, and bedding	[178]
Pineapple	Leaves	Steel rack of the helicopter, aeronautical component, automotive parts (interior panels and bumpers), and surfboards	[179]
Agave	Leaf	Building construction, offshore applications, naval construction, handicrafts, carpets, mats, ropes, and water lines	[179, 180]

plant fibers, aspect ratio on thermomechanical performances like as density, strengths, Young's modulus, Poisson's ratio, and thermal conductivity. However, there are two types of RVE techniques used for BCs modeling: (a) direct RVE and another one is (b) orientation averaging technique for discontinuous natural fiber-reinforced composites. In the case of direct RVE simulation, several natural fibers are surrounded by the polymeric matrix, whereas a single natural fiber is embedded by the polymeric matrix-like unit cell. A flax/epoxy BC modeling is shown in Fig. 12.

Mechanical properties of BCs

The mechanical properties of BC materials are highly important to attain expected performances. However, the properties depend on the behavior toward temperature, applied force, cooling/heating rate, deformations, and associated rates, and so on. Besides, the chemical composition, copolymerization, morphology, crosslinking, molecular weight, plasticization, types of filler materials with associated concentrations, etc., determine the mechanical performances of biopolymer composites [207–210]. There are different types of mechanical properties like tensile strength, tensile modulus, flexural strength/modulus of rupture (MOR), modulus of elongation (MOE), compressive strength, elongation at break (%), and so on that are needed to investigate the mechanical performances of BC materials [211–213]. Besides, the stress–strain relationship of the composite materials over different temperature and time is also very much signification for analyzing the rheology [214, 215]. However, the characterization of the BC materials depends on the type of materials and potential application areas. Conversely, mechanical properties of natural fibers are comparatively lower than that of artificial/synthetic fibers (like carbon, glass, etc.)-based composites. But, the mechanical performances of the biofiber-based composites could be tuned through modifying the fiber surface with various chemical modifications or using the most suitable additives. (Table 5) Different mechanical properties of the BCs are discussed below:

Table 6 Mechanical properties of different plant fiber-reinforced composites

Reinforcement/matrix	TS (MPa)	TM (GPa)	FS (MPa)	FM (MPa)	Elongation at break (%)	IBS (MPa)	Method	Ref
Flax/glass with phenolic resin	412.5 ± 12.7–392.5 ± 20.0	40.8 ± 1.4 – 39.7 ± 0.6	–	–	0.99 ± 0.04 – 0.96 ± 0.06	–	Compression molding	[231]
Hemp (35%)/ polyester	60.2	1.736	112.9	6.38	–	–	RTM	[232]
Jute/PP	56.71	1.82	77.32	4.34	–	–	Injection and extrusion molding	[233]
Ramie (5 layer)/Epoxy	99.04 ± 2.85	–	98.73 ± 5.98	–	–	–	Compression molding	[234]
Kenaf/PP	24.67	2.35	45.56	2.37	–	–	Injection molding	[235]
Sisal/epoxy	83.96 ± 6.94	1.58 ± 0.08	252.39 ± 12.11	11.32 ± 1.02	–	–	Hand lay-up	[236]
Sugarcane bagasse/PU	–	–	14.9	1.53	–	1.18	Hot-pressing	[237]
Sugarcane bagasse/ Portland cement	–	–	2.97	1.044	–	–	Pressing	[238]
Rice straw/LDPE	13.7	0.144	33.7	1.6	24.1	–	Injection molding	[239]
Bamboo/starch (C300)	45	–	58	–	–	–	Hot-pressing	[240]
Coir/polyester	16.46		29.22	–	–	–	Hand lay-up	[241]
Abaca-GFRP/epoxy	44.5	0.27	12.5	–	15.05	–	Hand lay-up	[242]
Pineapple/epoxy	80.12 ± 2.23	8.15 ± 0.23	~ 100	–	–	–	Hand lay-up	[243]
Coir/PLA	5	1.5	25	3.2	0.7	–	Hydraulic pressing	[244]
Rice straw/PP	33.2 ± 0.5	1.66 ± 0.025	36.5 ± 0.5	1.28 ± 0.027	23.9 ± 2.9		Injection molding	[245]
Reed/citric acid	–	–	12.51	2.45	0.54	17.98	Hot-pressing	[246]

TS tensile strength, *TM* tensile modulus, *FS* flexural strength, *FM* flexural modulus, *IBS* internal bonding strength, *GRRP* woven rovings

Figure 13 Test specimens prepared for BCs characterizations.

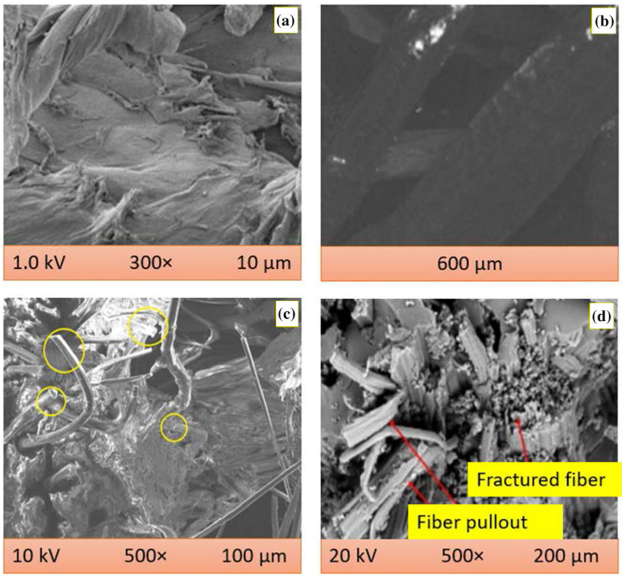


Figure 14 SEM morphologies of different BCs: **a** untreated coir/PP, **b** 70% sisal, 30% kenaf/ABS, **c** fractured flax/PLA, and **d** fractured jute/green epoxy composites. Adapted with permission from Elsevier [248–251]. Copyright Elsevier, 2010, 2017, 2018 and 2017.

Tensile, flexural, and compressive properties of BCs

The basic tests of BCs are also termed as tensile, flexural, impact, and compressive properties, which are used extensively to determine materials performances. In case of tensile test, various testing methods are used like EN 310 [216], ASTM D 638 [217], ASTM D 3039 [218]. The tensile properties of test specimens are measured with the extent of required force for breaking the sample along with the associated degree of breaking extensions [219]. The tensile strength, modulus, and elongation at break (%) are the principal properties of BCs that are found through a typical stress–strain curve. The stiffness of BCs is predicted by the tensile modulus. A sample length of 2t (thickness) + 50 in mm is used for sample length as per EN310 standard to prepare the test specimens. However, tensile performances of the BCs could be improved through modifying the surface treatment of natural fibers [220–222]. The tensile properties of some commonly used natural fiber-reinforced composites are provided in Table 6. The test specimen is supported on two sides, whereas the load is applied at mid-point until the sample is failed. Impact testing is another important parameter to assess the performances of the BCs in terms of unnotched test specimens. Testing standard ASTM D 4812–11 [223, 224] is implemented to perform this test on an impact measurement device in cantilever beams. Different testing techniques like 4 or 3-point bending characterization is conducted for this test. On the other hand, compressive strength indicates the withstanding capability of BC materials against applied loads to elongate or reduce size. The testing standard ASTM D 695-02a [225, 226] and ASTM D7137 [227, 228] is used for compressive strength analysis. The compressive properties of BCs depend on the fraction of fiber volumes and reinforcement architecture [229].

In the case of flexural properties, the capability against bending deformations of the BCs is measured. The moment of inertial and BC modulus are two principal parameters that the flexural properties depend on [149]. The prepared test specimen samples both for tensile and bending tests are illustrated in Fig. 13 and some associated mechanical properties are shown in Table 6. The increase in natural fiber content also increases the flexural properties of the BCs [149]. ASTM D 790 [230] and EN 310 testing standards are used for flexural properties investigations.

Physical properties of BCs

Water absorption, thickness swelling, and moisture content of BCs are some of the influential physical properties. Natural fiber-reinforced composites exhibited higher water absorption characteristics compared to synthetic fiber as the natural fibers contain enormous –OH, –COOH, –CO, and $-NH_2$ groups into their polymeric chain as cellulosic fibers

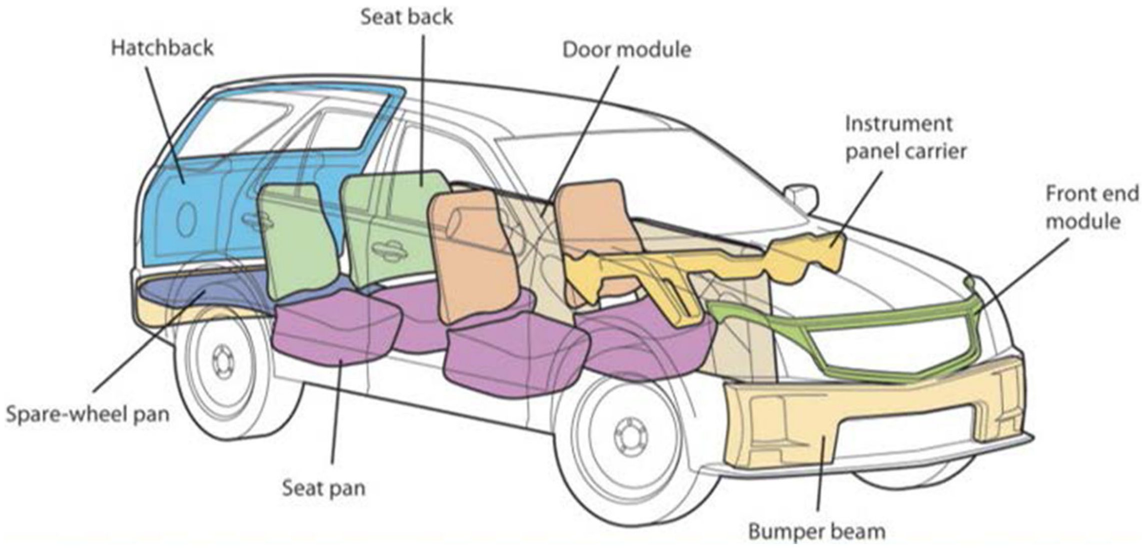


Figure 15 Thermoplastic composites made from long fibers for automotive parts/components. Adapted with permission from Elsevier [254]. Copyright Elsevier, 2007.

which are considered as hydrophilic compounds, whereas synthetic fibers like glass/carbon do not contain any similar hydrophilic chemical groups [62]. Besides, the treatment of natural fibers also significantly influences the moisture content of the BCs. Sanjay et al. [247] has reported that alkali-treated natural kenaf fiber-based composites exhibited 3.85% moisture absorption than the untreated composites (6.38%).

Morphological properties of BCs

The SEM test is a very influential characterization for BC materials to investigate the presence of natural fibers in the polymeric matrix system. Generally, the fibers could not be seen clearly as the surfaces are coated by thermosetting polymers strongly in the case of laminated composites [62]. However, in the case of thermoplastic composites, the fibers still could be appeared if the surface layer is fabrics but for polymers as the top layer is still not possible to find the fibers in un-fractured surfaces. But, the fractured surfaces obtained after tensile loading of plant fiber-reinforced BCs could easily exhibit the presence of fibers in the matrix system. Furthermore, the SEM photographs also provide information on fiber-to-polymeric adhesions characteristics. If the fiber materials are not compatible with the applied polymeric matrix, then this phenomenon could be assessed by the SEM photographs as well. In Fig. 14, the SEM morphologies of different BCs (both in fractured and before fractured) surfaces are illustrated.

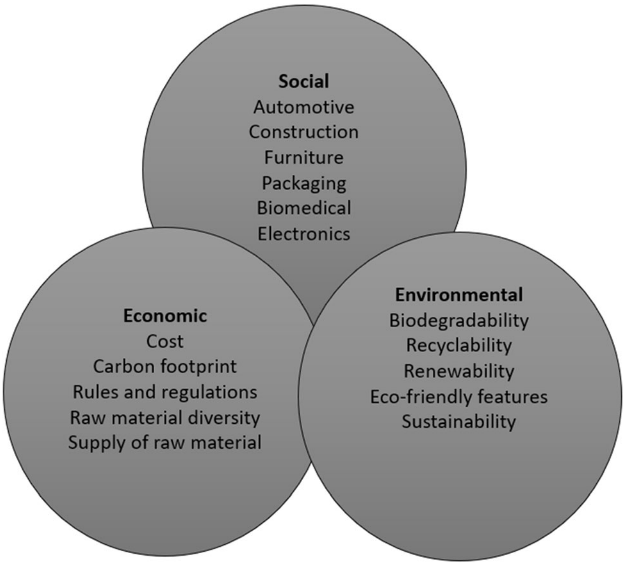


Figure 16 Sustainable requirements of products. Adapted with permission from Elsevier [267]. Copyright Elsevier, 2019.

Application of Plant fiber Composites

Cellulose-based plant fiber-reinforced polymer composites are lighter in weight, low-cost processing, and capable of producing in variable application forms [252]. Their densities are low, properties are comparable, molding flexibility is high and ecologically approachable, and even they can function as a feasible substitute to outdated fillers like calcium carbonate, glass, and mica. By modification of either compositing materials or plant fibers to be used, they can be fabricated for an extensive range of potential applications in the practical product (Table 5) for example fuel cell membranes, electro-active papers, biosensors, and controlled mechanisms of drug release. According to the view of using sustainable materials, automotive companies, especially the European industries, are utilizing plant-based fibers for their vehicle systems parts. It was observed that 20,000 tons of vegetable fibers were used by the transportation companies in 2010, which was increased to 50,000 tons by 2015 [253].

The application of BC was started in the twentieth century. The manufacturing companies are turning to use ecofriendly products that would reduce environmental impacts. So, the automotive companies are using BCs for different parts of their products (Fig. 15) to ensure environment-friendly and sustainable features. General Motors used the BCs in their floor mats of the cargo area and seated back for Chevrolet Trial Blazer and Cardilac De Ville [160]. BMW also implemented the natural fiber-based composites for their door panels, headliner panels, and noise insulation panels for the 3, 5, and 7 series [160]. Toyota has developed a spare cover from natural fiber-reinforced composites for its car of the RUAM 2003 model [255]. Honda has used bio-based composites for their pilot model car. Biocomposites developed from chitosan, PVA, and graphene oxide is also used for wound dressing purpose in the medical sector [256]. There was a significant alarming report for the 70% consumption of energy in automotive sectors related to their higher weight. So, weight reduction is going to be a significant concern for minimizing energy consumptions [257]. Audi A3 used hemp reinforced BCs for the side panels [253]. The lightweight building panels are also produced from natural fiber-based composites. A building

Table 7 Production volume, price, and employment opportunities of bio-based fibers worldwide. Adapted with permission from Elsevier [273]. Copyright Elsevier, 2020

Natural fibers	Estimated production (million)	Household (millions)	Employment (millions)	Production value (billions $)
Abaca	83,000	0.1	0.5	0.1
Bast fibers, other	1,90,000	0.25	1	0.3
Coir	9,70,000	1.28	6	1.3
Cotton lint	2,61,20,000	45	170	45
Fiber crops not specified elsewhere	2,80,000	0.37	2	0.4
Flax fiber and tow, ex scutching mill	3,10,000	0.01	0.01	0
Hemp fiber and tow	70,000	0.0	0.002	0.0
Jute, kenaf, and allied fibers	25,00,000	6	33	6
Kapok fiber	96,000	0.13	0.6	0.1
Ramie	1,00,000	0.13	1	0.1
Sisal, henequen, and similar hard fibers	2,10,000	0.04	0.2	0.0
Silk, raw	1,64,000	0.3	0.8	0.3
Wool, clean	10,80,000	5	10	5
Other, greasy weight	31,000	0.1	0.3	0.1
Total natural fibers	3,22,00,000	59	226	59

envelope was developed with thermal insulation property (0.27–0.30 Wm^2K) from BC materials when set with the framing profiles [258].

The economical and sustainable perspective of BCs

Ecofriendly production processes and recycling the waste materials are getting attention throughout the world for constantly raising rules and legislations against nonrenewable harmful materials. In this regard, the researchers are focusing on sustainable BCs productions. Plant fibers play a significant role in the life cycle of BCs. The life cycle assessment (LCA) approach of BCs is necessary to ensure the end-of-life treatment systems [259]. The sustainability of BCs could be analyzed by using the LCA approach in terms of environmental impacts during the different stages of product life cycles [260]. Around 55 million tons of plant-based forest and agro-based vegetable wastes were generated in European Union in 2016 [261]. These residues exist a vast potentiality for transforming into bio-based plastics, organic fertilizers, and foods. The manufacturing of natural fibers (9.55 MJ/kg) also consumes less energy compared to synthetic materials (like glass 54.7 MJ/kg) [262]. The BCs are considered to have less adverse effects than traditional petroleum-based plastics on the environment from the very beginning of their fiber extraction and up to the disposals during their entire period of life cycles. However, to use 100% bio-based materials is not also a very good concept always in terms of an economical point of view. But, the combination of both natural and synthetic materials is more viable to produce low-cost products as well [263, 264]. Products featured with sustainable characteristics, biodegradability, and renewability are escalating the market volume for the environmental awareness perspectives because plastic-based wastes are becoming a critical concern throughout the world nowadays which is shown in Fig. 16. Besides, the manufacturers are also getting continuous pressures from the governments, media, and environmental organizations to be more sustainable. The synthetic materials are getting replaced by natural fibers originated from renewable sources which are extensively available in nature. Recently, innovative BCs are developing and getting attentions to the manufacturers and consumers. The usage of plant fibers as the raw materials for BCs has been motivated the farmers as well to cultivate more plants which are playing a big role in reducing the greenhouse effect [265]. Different manufacturing industries (automotive, biomedical, construction, aerospace, and household) are using BCs for different parts of their products [3, 266].

Bioplastics encompassed a market volume of $3.94 billion in 2014 [51]. The annual production of plastics was 300 million tons in 2013, which was approximately increased by 200 times compared to 1950, which could be raised to a few times fold market after this century [268, 269]. It is also thought that near 93 million barrels of crude oil manufacturing could be required per day at the closure of this century. Besides, the natural fibers have created enormous employment along with a big market volume, as given in Table 7. The composites have potential attentions in the field of automotive, aerospace, and construction sectors intending to reduce the CO_2 emission and more sustainable, which is occupying the market volume by $26 billion in 2018 that is going to be raised for $41.4 billion within 2025 with a continuous growth rate of 6% [270, 271]. Still now, the applications of BCs to a greater extent are limited to the automotive sector, but it has still potentiality to be applicable for other industries as well. The products made from renewable sources are more competitive in the market comparing to the traditional items if they could offer similar or even little more performances along with better prices [267, 272]. So, the overall bio-based composite markets are booming for the increased customer demand throughout the world.

Conclusion

After considering a wide range of natural materials, plant-based fibers are one of the most potential fields of research in the direction of composite science due to low cost as well as environmental aspects. Various phenomena of plant-based natural fibers, particularly because of their bio-renewable traits and inherent ecofriendly characteristics, contribute a number of benefits over synthetic fibers such as glass, aramid, and carbon fibers to enhance the usage of BCs for diversified sectors (automotive, construction, aerospace, packaging, furniture, biomedical, and so on). The operative exploitation of diverse types of natural fibers and associated BCs has discoursed in detail in the current review paper. There is a cumulative petition from the green environment for materials with sound abatement capability as well as proficiency; therefore, the function of plant-based natural fibers over man-made fibers. However, the characteristics of these BCs are widely reliant on the possessions of individual fiber and the attraction between fiber polymer and matrix system. The enrichment of the specific functional properties of the composites can be reached employing chemical treatment of matrix and fiber either before and/or after composition. Analyzing this short review, applications of plant-based natural fiber-based composite could be an alternative potential composite material, especially for multifunctional purposes, which is highly plausible with lighter weight and low-cost features.

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Compliance with ethical standard

Conflict of interest The authors are declaring no conflict of interest for this review work.

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