

Review

Plant-Based Natural Fibre Reinforced Composites: A Review on Fabrication, Properties and Applications

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Abstract: The increasing global environmental concerns and awareness of renewable green resources is continuously expanding the demand for eco-friendly, sustainable and biodegradable natural fibre reinforced composites (NFRCs). Natural fibres already occupy an important place in the composite industry due to their excellent physicochemical and mechanical properties. Natural fibres are biodegradable, biocompatible, eco-friendly and created from renewable resources. Therefore, they are extensively used in place of expensive and non-renewable synthetic fibres, such as glass fibre, carbon fibre and aramid fibre, in many applications. Additionally, the NFRCs are used in automobile, aerospace, personal protective clothing, sports and medical industries as alternatives to the petroleum-based materials. To that end, in the last few decades numerous studies have been carried out on the natural fibre reinforced composites to address the problems associated with the reinforcement fibres, polymer matrix materials and composite fabrication techniques in particular. There are still some drawbacks to the natural fibre reinforced composites (NFRCs)—for example, poor interfacial adhesion between the fibre and the polymer matrix, and poor mechanical properties of the NFRCs due to the hydrophilic nature of the natural fibres. An up-to-date holistic review facilitates a clear understanding of the behaviour of the composites along with the constituent materials. This article intends to review the research carried out on the natural fibre reinforced composites over the last few decades. Furthermore, up-to-date encyclopaedic information about the properties of the NFRCs, major challenges and potential measures to overcome those challenges along with their prospective applications have been exclusively illustrated in this review work. Natural fibres are created from plant, animal and mineral-based sources. The plant-based cellulosic natural fibres are more economical than those of the animal-based fibres. Besides, these pose no health issues, unlike mineral-based fibres. Hence, in this review, the NFRCs fabricated with the plant-based cellulosic fibres are the main focus.

Keywords: green and eco-friendly composites; natural fibre reinforced composites; cellulosic fibres; mechanical properties; applications; biodegradable and sustainable

1. Introduction

After energy production, which contributes greatly to carbon emissions, the textile and fashion industry is considered the second most polluting industry due to generating huge amounts of wastewater, and tonnes of textile waste that is directly buried in landfills or incinerated [1–8]. In the textile industry, production of fibres plays a major role, where fibres are classified as synthetic or man-made fibres and natural fibres. Synthetic fibres are produced from non-renewable and petroleum-

based raw materials, which are not biodegradable [9,10]. On the other hand, natural fibres are fabricated from natural resources such as plants and animals, which are easily available, biodegradable, biocompatible and renewable [5,9–11]. The textile fibres are currently not only used in the traditional clothing and fashion industry but in the other industries or sectors, such as automobile, aircraft, marine, sports, and agriculture industries [1,2,12]. To satisfy these various application areas, the global production and use of synthetic fibres is significantly greater than that of natural fibres, with the view that the physicochemical properties of synthetic fibres can be modified based on the final application and the product's end-use requirement [5,13]. However, due to the complex chemical structures of synthetic fibres, it is difficult to reuse or recycle them after their lifetime. Therefore, they are mostly dumped into landfills or incinerated, which results in serious environmental impacts [14,15].

To overcome the environmental impacts and consequently meet the demand of textiles for different application sectors, the utilisation of natural fibre reinforced composites (NFRCs) is getting more attention in industry and in the academic research community [9,10]. The production and utilisation of the NFRCs will eventually enhance the eco-friendliness and sustainability of material production (Figure 1). Another reason for developing the NFRCs is their lightness, due to the lower density of natural fibres (generally ranged 1.2–1.6 g/cm³) compared to the synthetic fibres (e.g., glass fibre: 2.4 g/cm³) [16]. The NFRCs are also referred to “green composites,” “ecocomposites” and “biocomposites” where natural fibres are embedded with the thermosetting or thermoplastic polymers to fabricate the composites [9–11]. The NFRCs are composed of a polymer matrix (consisting of either a petroleum-based source or a natural biopolymer) and a reinforcing material (in the form of fibres or particles) [17]. The NFRCs can be classified into three groups, green, semi-green and hybrid composites, depending on the ratio of natural materials used as the reinforcing medium [17–20]. Green composites are when both the polymer matrix and reinforcing materials are procured from natural or renewable sources (e.g., PLA and hemp) [17,21,22]. The semi-green composites are composed of natural and synthetic polymers—with more natural materials [17–20]. The hybrid composites are made of a single polymeric matrix and two or more individual synthetic or man-made fibres, such as a composite structure fabricated with glass or carbon fibres [17–20]. Although developing a 100% bio-based composite is an ongoing attempt, it is difficult due to some undesirable properties associated with the natural fibres—e.g., high moisture absorption, the long and troublesome extraction processes and low thermal stability—which often negatively influence the ultimate mechanical properties of the composite materials [11,23,24]. Therefore, a feasible and tremendous effort is currently going on to develop composites wherein different percentages of natural fibres can be added to the polymeric matrices. These composites are low bio-based content composites (natural fibre content of <20%), medium bio-based content composites (natural fibre content of 21–50%) and high bio-based content composites (natural fibre content of 51–90%) [17,25,26].



Figure 1. The life cycle of biodegradable, natural fibre reinforced composites (Reprinted with permission from [27]; Copyright 2018 SAGE).

The NFRCs are environmentally friendly, biodegradable, biocompatible, renewable and cost-effective [5]. For example, these composites have the potential to replace steel in the automobile industry, which may reduce the total weight of a vehicle by around 25% and the consumption of nearly 250 million barrels of oil [5]. The NFRCs can be used in the production of bicycle frames, door and window frames, columns, ceilings and so on [28]. Besides, in recent years, along with the virgin natural fibres, the abundantly available short and non-spinnable waste natural fibres and recycled plastic materials have been used in fabricating the NFRCs. For example, waste oil plum fibres; wood flour and fibres; recyclable polymers (e.g., polyolefins); and short fibres of cotton, flax, sisal, jute, hemp and recycled plastics are used instead of virgin plastics to produce the bio-based green composites for applications wherein composites with strong mechanical properties are not required (e.g., panels, gardening products and packaging) [28–32].

Although some detailed reviews are available on the NFRCs [33–36], a single review covering the NFRCs' fabrication processes, the required properties of the natural fibres and the polymeric matrices, the detailed mechanical properties, the challenges associated with the fabrication of the NFRCs and their potential remedies with applications of the NFRCs is not present. Therefore, in this paper, we systematically review the fabrication procedures of natural fibre reinforced composites along with the physicochemical properties of the natural reinforcing materials and polymer matrices. The mechanical properties of the NFRCs, the factors affecting the mechanical properties of the NFRCs and their potential application areas are also summarised. As mentioned earlier, these composites go by many other names; we will mainly use natural fibre reinforced composites (NFRCs) or biocomposites in this review to avoid any misunderstanding of the readers. It is worth mentioning that among natural fibres, plant-based fibres are mostly used in the fabrication of NFRCs because of their price and safety. Therefore, the properties and applications of the natural fibre reinforced composites produced with the plant-based natural fibres are reviewed here.

2. Reinforcement and Polymer Matrix of Biocomposites

The prime objectives of fabricating the biocomposites include but not limited to the development of a new line of fibre composites to replace the use of plastics and other synthetic fibres that will not only be eco-friendly but sustainable throughout the manufacturing process and after the useful lifetime. Generally, the term “biocomposites” refers to fabricated composite materials where two or more constituents are joined together in which at least one element is obtained from natural or bio-based resources [17,37]. In a broad definition, it can be said that biocomposites can be formed in between wood and non-wood based natural fibres (e.g., hard and softwood, and cotton, jute and sisal fibres), in between biopolymers and natural fibres (e.g., PLA and sisal) or even in between biopolymers and natural fibres with synthetic or man-made fibres (PLA and glass fibres) [17,37–40].

Figure 2 [41–46] shows the tree diagram of reinforcement and matrix materials associated with the fabrication of the NFRCs. NFRCs are fabricated with combinations of natural reinforcing agents and polymer matrices. The natural fibres originating from the plant, animal and mineral sources can be used directly, or in chopped fibrous strands, nonwoven mats or fabric forms.

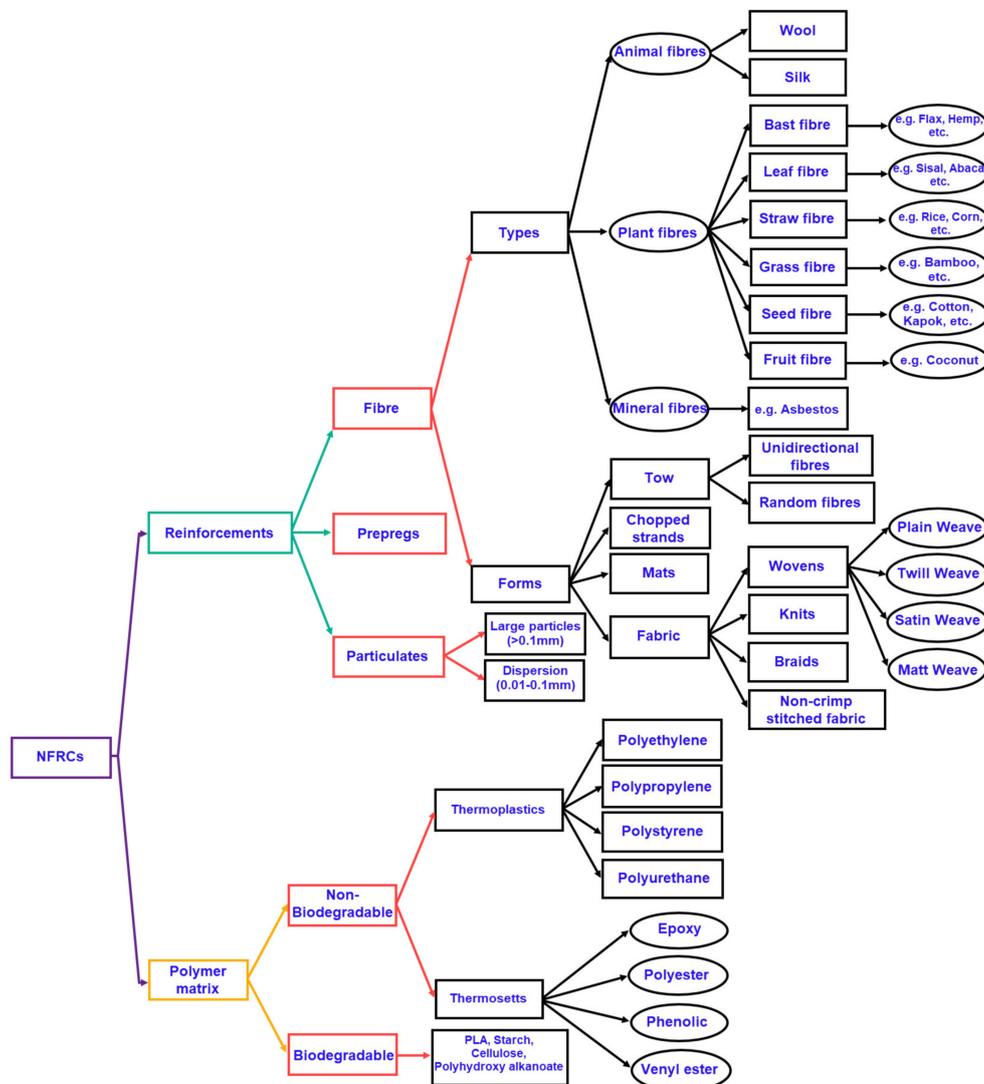


Figure 2. Composite constituent materials at a glance [41–46].

Natural fibres are broadly classified based on their origins, such as plant, animal and mineral sources (Figure 2). The plant fibres are collected from seeds (e.g., kapok, oil palm, cotton and coir), bast (e.g., ramie, hemp, flax, jute and kenaf), straw (e.g., wheat, rice and corn), wood (e.g., soft and

hardwood), grass (e.g., bamboo and bagasse) or leaves (e.g., pineapple, sisal and abaca). The animal fibres, also known as the protein fibres and mostly used in the textile industry, are the second most widely available natural fibres after the plant-based fibres, and are obtained from sheep, alpacas, cashmere, silk, chickens and ducks [11,47–49]. Generally, the animal fibres are used in particles or chopped fibres while producing the biocomposites [9,11,24]. The protein fibres possess some excellent properties, such as inherent fire retardancy and thermal stability. However, the animal fibres are not widely used in the commercial production of the NFRCs due to the higher prices of the protein fibres (e.g., silk costs 2.6–40.0 US\$/kg) compared to the plant fibres (e.g., hemp costs 1.0–2.1 US\$/kg) [11,50,51]. Mineral fibres are nonmetallic and inorganic fibres produced from minerals. Asbestos and glass are the most used mineral sources for fabricating biocomposites. However, the application of asbestos fibres is currently banned due to their extensive carcinogenicity and other health issues [21,24]. As mentioned above, due to some issues associated with the animal and mineral fibres, such as cost and safety, natural plant-based fibres are mostly used in the fabrication of NFRCs, which is the focus of this study.

2.1. Plant-Based Natural Fibres

The most commonly used plant fibres are shown in Figure 3. The main components of the plant fibres or cellulosic fibres are cellulose, hemicellulose and lignin (Table 1) [52,53]. The amounts of cellulose, hemicellulose and lignin differ in the plants owing to their maturity, location of growth, environment and even species.

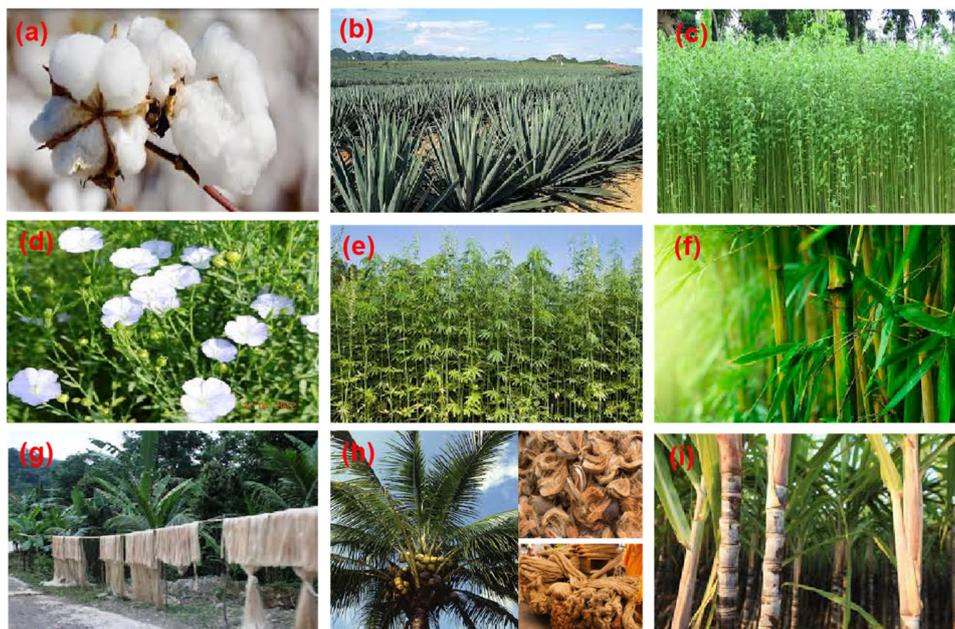
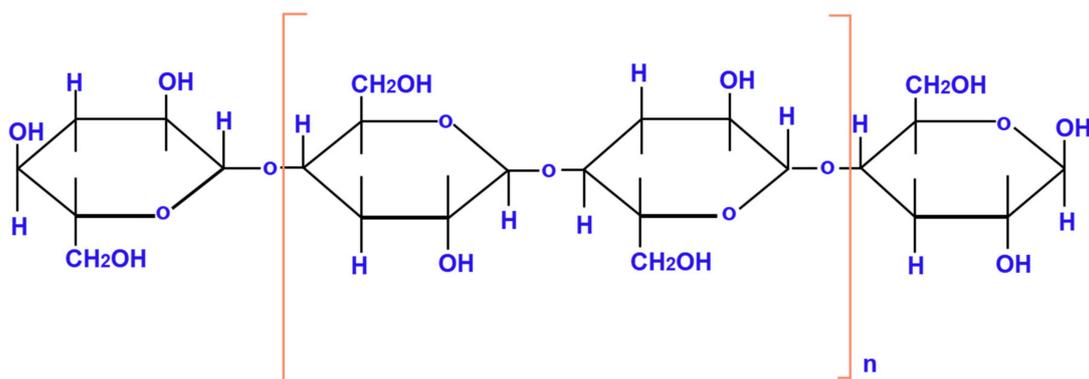


Figure 3. Natural fibre plants: (a) cotton; (b) sisal; (c) jute; (d) flax; (e) hemp; (f) bamboo; (g) banana; (h) coir; (i) sugar cane.

Cellulose, as shown in Figure 4, is a natural polysaccharide wherein D-glucopyranose rings are connected with β (1→4) glycosidic linkages [10,53]. All plant fibres possess a crystalline structure with a nearly 65–70% cellulose that consists of C, H and O (having a common formula of $(C_6H_{10}O_5)_n$) [10,52]. Additionally, the final properties and characteristics of cellulosic fibres are modified with the presence of lignin and further non-cellulosic constituents. Due to the presence of a higher proportion of hydroxyl groups and hygroscopic nature, one of the important properties of the plant-based fibres is their higher moisture absorption capability, which is very often an essential requirement for the fabricated composites [22,52]. The chemical constituents and physical and mechanical properties of most widely used plant-based natural fibres are presented in Table 1.

Table 1. Chemical constituents and physical and mechanical properties of the plant-based natural cellulosic fibres [10,21,25,52,54–60].

Fibres	Composition			Physical Properties			Mechanical Properties		
	Cellulose (wt.%)	Hemicellulose (wt.%)	Lignin (wt.%)	Moisture Content (wt.%)	Density (g/cm ³)	Diameter (µm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Abaca	56–63	20–25	7–9	5–10	1.5	150–180	430–980	12	3–10
Bagasse	55.2	16.8	25.3	20–28	1.2	320–400	20–290	19.7–27.1	1.1
Bamboo	26–43	30	21–31	11–17	0.9	10–30	250–850	9.8	5.6–8.6
Banana	63–64	17–19	3–5	8–10	1.35	160–200	355	33.8	53
Coir	36–43	0.15–0.25	40–45	8	1.15–1.46	100–460	131–220	4–6	15–40
Cotton	82–90	5.7	-	7.85–8.5	1.5–1.6	12–38	287–800	5.5–12.5	7–8
Flax	71	18.6–20.6	2.2	8–12	1.5	40–600	88–1500	27.6	2.7–3.2
Hemp	70.4–74.4	17.9–22.4	3.7–5.7	6.2–12	1.47	25–500	550–900	70	1.6
Henequen	58–60	28–30	7–8	10–12	1.4	160–180	430–580	15–20	3–4.7
Jute	61–71.5	13.6–20.4	12–13	12.5–13.7	1.3–1.49	25–200	393–800	13–26.5	1.16–1.8
Kapok	35–50	22–45	21.5	9.86	0.29	30–36	50–90	2–5	1.8–4.3
Kenaf	35–57	21.5	15–19	6.2–12	1.2	30–50	295–930	53	1.6–6.9
Oil palm	45–48	32–35	16–18	12–15	0.7–1.55	150–500	248	3.2	25
Pineapple	70–82	-	5–12	14	1.5	105–300	170–1672	82	1–3
Sisal	67–78	10–14.2	8–11	10–22	1.45	50–200	468–700	9.4–22	3–7
Ramie	68.6–76.2	13.1–16.7	0.6–0.7	7.5–17	1.55	35–60	400–938	61.4–128	1.2–3.8
Rice	41–57	33	8–19	14	0.9–1.5	15–25	100–160	0.3–2.6	5.4–10.6
Wheat	39–45	15–31	13–20	18–20	1.1–1.3	20–40	90–150	0.2–2.2	3.5–6.6

**Figure 4.** The chemical structure of cellulose. Reprinted with permission from [52]; Copyright 2011 Elsevier.

2.2. Polymer Matrix

Biocomposites are fabricated with the addition of plant-based natural fibres and polymer matrices (Figure 2). Therefore, it is very important to choose correct polymer matrices for the production of the biocomposites. Polymers are the macromolecules composed of single or many repeating units [61]. The polymeric chains in the matrix can be arranged in a unidirectional way or randomly result in a crystalline and amorphous structure, respectively. The polymers are generally divided into thermoplastic and thermosetting polymers (Figure 2) [62]. Thermoplastic polymers (e.g., polypropylene, polycarbonate, polyimides, polyethylene terephthalate) bonded with weak van der Waals forces, are widely used in manufacturing composites where both the weaker and stronger mechanical properties are required [61,62]. These polymers show outstanding toughness and resistance to wear and tear [61]. On the other hand, the thermosetting polymers (e.g., epoxy, silicone, polyurethane) are moulded into 3D networks along with strong covalent bonds and cross-linking, which makes them tough. These polymers possess higher thermal stability, creep and chemical resistance, easy processability and good wetting properties [61,63]. In general, the synthetic polymers are neither biodegradable nor flame retardant (suppressed by the addition of the nature-based polymers). Some of the key properties of the polymer matrices are illustrated in Table 2.

Table 2. Properties of polymer matrices [61,64–66].

Polymer	Density (g/cm ³)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Melting Temperature (°C)	Thermal Conductivity (W·m ⁻¹ ·K ⁻¹)	Total Heat Release (kJ/g)
Polyethylene (PE)	0.93	15	0.8	105–115	0.33–0.51	41.6
Polypropylene (PP)	0.92	40	1.9	130	0.1–0.2	41.4
Polyacrylonitrile (PAN)	1.18	57	2.7	300	1.0	13.3
Polycarbonates (PC)	1.2	70	2.6	157	0.19	20.3
Polystyrene (PS)	1.1	40	3	240	0.03	38.8
Polymethyl methacrylate (PMMA)	1.18	47	2.2	130	0.20	24.3
Polyvinyl chloride (PVC)	1.4	51	2.4	160	0.19	11.3
Polyvinyl acetate (PVA)	1.19	40	1.7	200	0.31	21.6
Polylactic acid (PLA)	1.2–1.4	50	3.5	150–160	1.13	14.2
Polyethylene terephthalate (PET)	1.38	55	2.7	260	0.15	15.3

3. Fabrication of Biocomposites

The fabrication process of the natural fibre reinforced composites (NFRCs) refers to the processes of preparing the preforms and then reinforcing the preforms with the polymer matrices [67]. The details of composite constituent (type, forms, etc.) are shown in Figure 2 [41–46]. There are a wide variety of processing techniques used to fabricate the composite materials. Application conditions for each of these techniques are quite different. Different types of composite fabrication methods can be classified according to the methods of a polymer matrix and reinforcement application to the mould, or according to the curing methods. However, all of these techniques can be broadly classified as open moulding or closed moulding techniques based on the application conditions of reinforcement and polymer matrix materials [68–73]. Open moulding is when the resin is exposed to the atmosphere during curing, and closed moulding is when the resin is not exposed to the atmosphere [74,75]. Each of these techniques has various application methods, as shown in Table 3 [42]. The composite fabrication technique is selected based on the constituent materials, the availability of the required tools and the properties required for the ultimate composite structures [76]. However, both the open and closed moulding techniques possess some benefits and drawbacks. Open moulding techniques are the most orthodox means of fabricating composites. They have been widely used because of their simplicity, low processing costs, unsophisticated techniques and variety of suitable reinforcements and laminating systems. Nevertheless, well-trained and highly skilled operators are essential to open moulding techniques to ensure the laminate quality, especially the void content and fibre volume fraction of the composite laminates [77]. On the other hand, the closed moulding techniques are preferred for making 3-dimensional composite parts of better quality, for less material waste and for perfect and aesthetic finishes of the parts [69,78,79]. This is mostly an automated moulding technique with reduced material, labour and waste disposal costs, and greater productivity. Compression moulding [80], extrusion moulding [81,82] and injection moulding [83–85] are the most used open moulding techniques for the thermoplastic composites. Hand layup [86,87], resin transfer moulding (RTM) [88], vacuum-assisted resin transfer moulding (VaRTM) [89] and resin film infusion (RFI) [90] are used for the production of thermosetting composites.

Table 3. Various types of open and closed moulding techniques [42].

Composite Moulding	
Open Moulding	Hand layup
-	Spray-up
-	Filament winding
Closed Moulding	Vacuum bag moulding
-	Resin Transfer Moulding (RTM)
-	Vacuum-assisted resin transfer moulding (VaRTM)
-	Resin film infusion, RFI
-	Compression moulding
-	Injection moulding
-	Pultrusion moulding

Figure 5a shows the two most popular open moulding techniques named hand lay-up and spray-up techniques, which are most suitable for the large composite components such as boat hulls, turbine blades, large container tanks, swimming pools and various automotive parts [91]. In the hand lay-up technique, reinforcement materials and the polymer matrix are applied manually onto an open mould surface, one by one until the desired thickness of the component is obtained by successive layers [92,93]. On the other hand, in the case of the spray-up technique, the reinforcement fibres in the form of chopped strands and the polymer matrices are sprayed using spray gun onto an open mould surface until the desired thickness of the composite lamination is obtained [44]. In fact, the spray-up technique is the automated version of the traditional hand lay-up technique.

Figure 5b represents the VaRTM composite fabrication process. Vacuum-assisted resin transfer moulding (VaRTM) is one of the most frequently used closed moulding processes in the fibre reinforced polymer composite industry. In this technique, the mould is filled with the reinforcement fibres and then closed, and simultaneously the air is pumped out and the polymer matrix is allowed to flow in to impregnate the fibres [94]. The reinforcement fibres are applied in a mould of the same geometry as the size and area of the required composite material [95]. The composite parts manufactured by this method possess fewer void parts with good surface finishes [96,97]. Currently, this fabrication technique is undergoing a wide variety of developments to produce more complex composite parts with the desired finishes at reasonable cost [95].

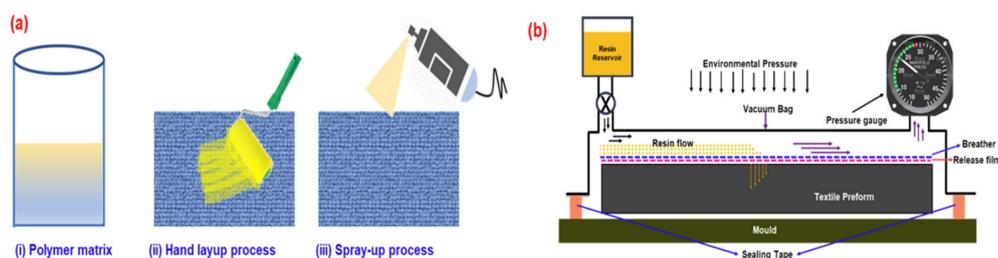


Figure 5. Composite moulding techniques. (a) Open moulding techniques: (i) polymer matrix; (ii) hand layup process; (iii) spray-up process (Reprinted with permission from [93]; Copyright 2018 Informa UK Limited). (b) Closed moulding technique: vacuum-assisted resin transfer moulding (VaRTM) (Reprinted with permission from [89]; Copyright 2012 Elsevier).

4. Mechanical Properties of the Biocomposites

The interfacial adhesion between the cellulosic fibre and polymer matrix sways the composite properties. The composites show better physicochemical properties if suitable interactions between the fibre and the matrix are provided [68,98]. Furthermore, fibre types, length, diameter, density, modulus, strength, fibre orientation [99–101] and weave structures [102–104] significantly control the mechanical properties of NFRCs. While NFRCs are fabricated using the hydrophilic cellulosic fibres and the hydrophobic polymer matrices, very often they result in poor interfacial adhesion [105] and

consequently poor mechanical properties [106–108]. Therefore, investigations have been carried out to enhance the adhesion between the fibres and the polymeric matrix through adopting some techniques such as reinforcement fibre surface modification and matrix modification [109–111]. To this end, the fibres are subjected to various chemical treatments [112,113], such as alkali treatment [114–117], silane treatment [118–123], esterification [124–127], acid treatment [128] or hybridization with different fibres [129–136], before reacting with the matrix materials.

Asumani et al. [119] used alkali-treated, kenaf, short-fibre nonwoven mats to fabricate kenaf-polypropylene composites by compression moulding technique and demonstrated improved mechanical properties of the composite material. The composites showed enhancements of 25%, 11% and 10% for tensile strength, modulus and flexural strength, respectively. Furthermore, alkali-silane combined treatment of kenaf fibre resulted in 75%, 94% and 50% increases in tensile strength, modulus and flexural strength of the composite, respectively. Similarly, Wambua et al. [137] applied the randomly oriented kenaf fibres and compared the composite properties to that of glass mat-polypropylene composites. Although the tensile modulus of kenaf-polypropylene composite was slightly higher (9.7%), the tensile strength, flexural strength, modulus and impact strength were lower (6.7%, 52%, 50% and 74%, respectively) than those of glass fibre mat-polypropylene, which might have been due to the lower interfacial bonding strength between the fibre and matrix. Cavalcanti et al. [138] investigated the cellulose-based composite that was manufactured using the hand layup technique, where jute, curaua and sisal fibres were the reinforcing agents and epoxy was the polymeric matrix. Pure jute fibre and jute blended with curaua and sisal fibres were chemically treated with (i) alkali and (ii) combination of alkali and silane for 1 h. Afterwards, it was found that the combined alkalisation and silanisation of jute fibre enhanced both the tensile strength (8.4%) and flexural strength (14%). Besides, the alkali treatment on the jute-sisal blended fibre reinforced composite demonstrated the maximal improvements. Singh et al. [139] investigated the influence of curing temperature on jute-epoxy composite properties. The jute woven preforms were used as the reinforcements and the hand layup fabrication method was applied, followed by the compression moulding technique. The authors concluded that 100 °C for flexural strength and 80 °C for impact strength are the optimum curing temperatures that yield the maximum output. Table 4 presents the literature available on natural fibre reinforced polymer composites; it summaries the fabric/matrix modifications and their effects on associated mechanical properties.

Table 4. Investigation of the mechanical properties of various natural fibre reinforced composites (NFRCs).

Reinforcement Fibre	Fibre Type	Matrix	Treatment (Fibre/Matrix Modification)	Fabrication Technique	Properties					Ref.
					Tensile Properties		Flexural Properties		Impact Strength (KJ/m ²)	
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)		
Kenaf fibre (30%)	Short fibre nonwoven mats	Polypropylene	Alkali treatment (5%NaOH)	Compression moulding	25%↑	11%↑	10%↑	-	-	[119]
			Alkali-silane treatment (5%NaOH)		75%↑	94%↑	50%↑	-	-	
Hemp fibre (30%)	Aligned fibre	Polylactic acid	Compared to neat polylactic acid	Compression moulding	76.5%↑	201%↑	16%↑	58%↑	39.1%↑	[140]
			alkali treatment (4 wt.% NaOH)		6%↑	17%↑	8%↑	14%↑	17.5%↑	
Flax fibre	Uni-directional (UD)	Epoxy	Hybridization with UD carbon fibre	Compression moulding	-	-	1.7%↑	45.1%↑	-	[141]
	Cross-ply (CP)				282%↑	170.5%	3.3%↑	42.9%↑	-	
Sisal fibre	-	Polyethylene	Treated with 3% of stearic acid.	Compression moulding	-	-	-	-	-	[142]
Vakka fibre	Unidirectional and continuous fibre	Polyester	Compared with sisal/polyester	Hand lay-up method	32%↑	12%↑	4.4%↓	35%↑	-	[143]
			Compared with banana/polyester		8.4%↑	66%↑	2.6%↑	62.7%↑	-	
			Compared with bamboo/polyester		45.7%↓	20%↓	26.2%↓	9%↓	-	
Jowar fibre	Unidirectional and continuous fibre	Polyester	Compared with sisal/polyester	Hand-lay-up method	89.3%↑	44.7%↑	34.7%↑	216.1%↑	-	[144]
			Compared with bamboo/polyester		1.8%↓	10.9%↑	4.3%↑	112.7%↑	-	
Alfa fibre	Crushed fibres	Polypropylene	Fibre esterification treatment	Heated two roll mill mixing and hot press moulding method	-	35%↑	-	-	-	[145]
Sansevieria cylindrica fibres	Chopped fibre	Polyester	Alkali treatment on fibre	Compression moulding	8.7%↑	0.3%↑	22.3%↑	8.8%↑	1.1%↑	[146]
			Benzoyl peroxide treatment on fibre		13.8%↑	0.7%↑	51.9%↑	23.8%↑	5.8%↑	
			Potassium permanganate treatment on fibre		87.3%↑	11.9%↑	79.9%↑	37.5%↑	147.7%↑	
			Stearic acid treatment on fibre		11.2%↑	0.1%↑	63.1%↑	25%↑	3.2%↑	
Coir fibre (20 wt.%)	Crushed fibre	Polyethylene	Sodium hydroxide (NaOH) treatment of fibre	Heated two roll mill mixing and hot press moulding method	6%↓	10%↑	-	-	-	[147]
			Silane treatment of fibre		16%↑	4%↓	-	-	-	

Table 4. Cont.

Reinforcement Fibre	Fibre Type	Matrix	Treatment (Fibre/Matrix Modification)	Fabrication Technique	Properties					Ref.
					Tensile Properties		Flexural Properties		Impact Strength (KJ/m ²)	
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)		
			Dodecane bromide treatment of fibre		6%↑	24%↑	-	-	-	
Sisal fibre (30 vol.%)	Randomly oriented fibres	Polypropylene	Compared to glass mat polypropylene composites	Compression moulding	6.7%↑	14.5%↓	55%↓	59%↓	50%↓	
Kenaf fibre (30 vol.%)					6.7%↓	9.7%↑	52%↓	50%↓	74%↓	
Hemp fibre (30 vol.%)					62.5%↑	9.7%↑	10%↓	14%↑	52%↓	[137]
Jute fibre (30 vol.%)					10%↓	42%↓	42%↓	36%↓	72%↓	
Coir fibre (30 vol.%)					68.75%↓	79%↓	53%↓	86%↓	59%↓	
Sisal	Long fibre rovings	Polypropylene	Addition of 2 wt.% maleated polypropylene	Long fibre thermoplastics processing and compression moulding	-	-	63%↑	53.3%↑	-	
Jute					-	-	38%↑	38.1%↑	-	[75]
Flax					-	-	97.5%↑	106.7%↑	-	
Sisal (20 wt.%)	Chopped fibre strands	Glycerol/thermoplastic starch	Compared to neat thermoplastic starch	Roll mill mixing and hot press moulding method	115%↑	1410%↑	-	-	-	
Hemp (20 wt.%)					208%↑	1720%↑	-	-	-	[148]
Sisal (20 wt.%)			3.6%↓		1.3%↓	-	-	-		
Hemp (20 wt.%)			30%↓		7.7%↓	-	-	-		
Kenaf fibre	Chopped fibre strands	Polyester	Magnesium hydroxide impregnation with fibre	Vacuum bag resin transfer moulding method	54.8%↑	-	-	-	-	
			Magnesium hydroxide impregnation with fibre and compared to the glass-fibre sheet moulding compound		19.5%↓	21.8%↓	-	-	-	[149]
Oil palm fibres	Fibre mats	Epoxy	Loading jute fibre	Hand lay-up technique	68%↑	48%↑	-	-	-	[150]
Jute fibres	Cross-ply (CP)	Epoxy	Loading banana fibre	Hand-lay-up technique	14%↑	9%↑	4.6%↑	2.4%↑	35.7%↑	[151]

Table 4. Cont.

Reinforcement Fibre	Fibre Type	Matrix	Treatment (Fibre/Matrix Modification)	Fabrication Technique	Properties					Ref.
					Tensile Properties		Flexural Properties		Impact Strength (KJ/m ²)	
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)		
Oil palm fibres	Chopped fibre strands	Phenol formaldehyde	Fibre chemical modification: mercerisation	Closed and hot press moulding method	5.4%↓	13%↑	53.1%↑	3.3%↓	-	[152]
			Fibre chemical modification: acetylation		48.6%↓	30.4%↓	26.5%↓	37.7%↓	-	
			Fibre chemical modification: peroxide treatment		5.4%↓	2.2%↓	44.9%↑	29.5%↑	-	
			Fibre chemical modification: permanganate treatment		8.1%↑	4.3%↑	12.2%↑	23%↑	-	
			Fibre chemical modification: silanization		59.5%↓	39.1%↓	53.1%↓	60.7%↓	-	
			Fibre chemical modification: acrylation		51.4%↓	47.8%↓	40.8%↓	41%↓	-	
			Fibre chemical modification: acrylonitrile grafting		29.7%↓	30.4%↓	6.1%↑	18%↓	-	
			Fibre chemical modification: latex coating		64.9%↓	52.2%↓	67.3%↓	77%↓	-	
			Peroxide treatment on resin	-	8.7%↓	10.2%↑	-	-		
Coir fibre	Randomly oriented fibres	Epoxy	Alkali treatment (5 wt.% NaOH solution)	Hand lay-up followed by the vacuum bagging technique	17.8%↑	6.9%↑	16.8%↑	6.5%↑	-	[153]
Jute fibre	Plain woven fabric	Polylactic acid	Compared to Jute/Polypropylene	Hot-press technique	52.6%↑	119%↑	-	130.8%↑	-	[154]
Sisal			Compared to sisal/polypropylene		21.6%↑	57%↑	-	84.4%↑	-	
Glass			Compared to glass/polypropylene		29.5%↑	47%↑	-	133.3%↑	-	
Jute	Bidirectional woven mat	Epoxy	Alkalization	Hand lay-up technique	-	4.7%↑	-	9%↓	19.6%↑	[138]
Jute + Curaua			Mixed (alkalization + silanization)		8.4%↑	9.6%↑	-	14%↓		
			Alkalization		9.2%↓	18.8%↓	13%↓	12%↓	25.4%↓	
			Mixed (alkalization + silanization)		1.3%↓	-	22%↑	75%↑	-	

Table 4. Cont.

Reinforcement Fibre	Fibre Type	Matrix	Treatment (Fibre/Matrix Modification)	Fabrication Technique	Properties					Ref.	
					Tensile Properties		Flexural Properties		Impact Strength (KJ/m ²)		
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)			
Jute + Sisal			Alkalization			12%↑	54.4%↑	-	21%↑	77.1%↑	
			Mixed (alkalization + silanization)			2.4%↑	9.1%↑	-	18%↓	-	
Jute	Combed unidirectional fibres	Epoxy	Surface treatment	Hand layup followed by compression moulding method		141.3%↑	-	4.7%↑	-	84%↓	[155]
Sisal						55.7%↑	-	10.8%↑	-	70.6%↓	
Banana						182.4%↑	-	10.3%↑	-	81.4%↓	
Rice husks (40% w/w)	Particles	Polystyrene	Compared with pure polystyrene	Mechanical stirring and single roller pressing		-	5114%↑	-	-	-	[156]
Jute fibre	Continuous fibre	Polyester	Compared with neat polyester with no reinforcement	Hand lay-up technique		48%↑	100.5%↑	18.1%↑	110.6%↑	49%↑	[157]
Bamboo fibre						81.6%↑	99.4%↑	34.2%↑	118.7%↑	108.5%↑	
Glass-Jute fibre						118.3%↑	121.3%↑	61.4%↑	171.5%↑	245.4%↑	
Glass-Bamboo fibre						146.8%↑	135%↑	70.3%↑	183.7%↑	360.7%↑	
Jute fibre	Woven preforms	Epoxy	Effect of curing temperature and compared with neat matrix	Hand lay-up followed by compression moulding technique		121.2%↑	50%↑	Max 41.8 at 100 °C	-	Max 3.5 J at 80 °C	[139]
Tapsi fibre (15 gms)	Continuous fibre	Epoxy	Alkali treatment (NaOH) and compared with KOH treatment	Hand lay-up method		20%↑	-	3.6%↑	-	-	[158]
Elephant grass fibre (20%)	Chopped fibre strands	Polylactic acid	Untreated and Compared with pure PLA	Injection moulding technique		21%↑	124.8%↑	17.5%↑	-	129.5%↑	[159]
			Untreated and compared with Jute/PLA			15.5%↑	-	24.3%↑	-	-	
			Untreated and compared with Sisal/PLA			5.5%↑	-	Slightly higher	-	-	
			Chemical treatment: mercerization and bleaching and compared with pure PLA			24%↑	149.6%↑	22%↑	-	Slightly higher	

Table 4. Cont.

Reinforcement Fibre	Fibre Type	Matrix	Treatment (Fibre/Matrix Modification)	Fabrication Technique	Properties					Ref.
					Tensile Properties		Flexural Properties		Impact Strength (KJ/m ²)	
					Strength (MPa)	Modulus (GPa)	Strength (MPa)	Modulus (GPa)		
			Chemical treatment: mercerization and bleaching and compared with Jute/PLA		18.14%↑	-	Slightly higher	-	-	
			Chemical treatment: mercerization and bleaching and compared with Sisal/PLA		Slightly higher	-	4%↑	-	-	
			Chemical treatment: mercerization and bleaching and compared with untreated grass/PLA		-	-	28%↑	-	-	
Tossa jute fibre	Commercially available fibre	Epoxy	Fibre corona treatment	Compression moulding	-	-	30%↑	-	-	[160]
Flax fibre	Randomly oriented fibre	Polyester	Fibre plasma treatment	Compression moulding	-	16.5%↑	-	-	-	[161]
kraft fibre	Randomly oriented fibre	Polypropylene	Fibre-beating treatment	Extrusion moulding	10%↑	-	-	-	-	[162]
Jute fibre	Chopped fibre strands	Vinyl ester	Fibre alkaline treatment	Compression moulding	-	-	35%↑	23%↑	-	[163]
Hemp fibre	Randomly oriented fibre	Polypropylene	Fibre silane treatment	Compression moulding	4%↑	-	2%↑	-	-	[164]
Flax fibre	Randomly oriented fibre	Polypropylene	Fibre acetylation treatment	Injection moulding	35%↑	-	35%↑	-	-	[165]
Sisal fibre	Chopped fibre strands	Polystyrene	Fibre benzylation treatment	Compression moulding	91%↑	-	-	-	-	[166]
Jute fibre	Randomly oriented fibre	Polypropylene	Fibre treated by a maleated coupling agent	Compression moulding	15.4%↑	22.4%↑	-	-	-	[167]
Hemp fibre	Randomly oriented fibre	Polypropylene	Fibre fungal treatment	Injection moulding	22%↑	-	-	-	-	[168]
			Fibre fungal and alkaline treatment		22%↑	-	-	-	-	

Factors Affecting the Mechanical Properties of Biocomposites

Many factors, such as type of polymer matrix and the types associated fibres; the fibre's origin, processing and forms; the fibre dispersion; the distribution in the matrix; the orientation; the fibre–matrix interfacial interaction; and the techniques used in the composite's fabrication, directly affect the mechanical properties of the biocomposites [169–174]. Besides, as the strength of reinforcement fibre is higher than that of the matrix material, the strength of a biocomposite is more dependent on the fibre rather than the matrix [175–178]. Therefore, the strength of a biocomposite can be enhanced by increasing the amount of fibre in the composite structure to a certain extent [179,180]. On the other hand, when the amount of fibre exceeds the limit, the load transferred through the interface reduces, and the amount of porosity in the composite increases, which results in a greater reduction in the strength and stiffness of the composite material [179]. Moreover, with the increment of fibre content into the composite structure, the water uptake of the composite increases, which very often degrades the mechanical properties of the composite material [181–183]. Along with the amount of fibre content, the length of the reinforcement fibre plays an important role in the mechanical properties of the composite [24]. The higher the aspect ratio of the fibre, the better its load-bearing capacity [184]. However, it should be noted that a very long fibre can become entangled, resulting in non-uniform distribution of the fibre and the reinforcement [185]. The matrix is also an important constituent of the composite that protects the fibre's surface from externally applied forces. The polymer matrix transfers the forces externally applied to the composite to the reinforcement materials, and thus enhances the composite's longevity [186]. With the increased interfacial interaction between the fibres and the matrices, the biocomposites become stronger. As the applied load is transferred from the matrix to the reinforcement materials, the interfacial bonding is all important and is the true indicator of the composite properties [170,187]. To increase the interfacial bonding between the fibre and the matrix, it is necessary to improve the hydrophobicity of the fibres, the interfacial bonding between matrix and fibre and the roughness [188]. Bonding between fibre and matrix is usually enhanced by a few mechanisms, such as mechanical interlocking, chemical bonding, electrostatic bonding and inter-diffusion bonding [189–195]. Besides, the other factors such as temperature, pressure, time and resin viscosity seriously affect the properties of the biocomposites [139,196–198].

5. Biodegradability of the Biocomposites

The natural fibre reinforced composites (NFRCs) show excellent biodegradability compared to the synthetic fibre-based materials and composites, which is one of the major aspects of fabricating NFRCs [199,200]. In general, the biodegradable materials are degraded and converted into CO₂, H₂O, hydrocarbons, methane and biomass under the aerobic or anaerobic conditions, due to the chemical or biological reactions [200–202]. In most of the cases, the material biodegradability is tested by the soil burial method (ASTM D5988/D5338 or ISO 14855) and the results are expressed by the weight loss (%) [199,203–206]. Different factors such as the molecular weight, chemical structure, glass transition temperature (T_g), melting temperature (T_m), mechanical behaviour, crystallinity and crystal structure potentially impact the NFRC's biodegradability [199,203]. For example, a polymer with high crystallinity and a high melting temperature shows lower biodegradability—i.e., lower weight loss (%) [200,203]. A study over a 3-month period revealed that the biodegradability of the lyocell incorporated polyester composites is higher (75%) than that of the pure polyester, which might be due to the presence of natural lyocell fibre [207]. In another study, the biodegradability test of the kenaf/PLA composites using the garbage-processing machine showed the weight loss of 38% within one-month of composting [208]. Recently, Wu et al. found that the use of 40 wt.% palm fibre (PF) as a reinforcement with the polyhydroxyalkanoate (PHA) matrix increased the rate of biodegradation (~90%) compared to pure PHA (~20%) [209]. Similarly, the study of Mittal and Chaudhary revealed that the biodegradability of the epoxy resin increased while using the nature-based pineapple and coconut fibres as reinforcements with the epoxy resin. Pure epoxy exhibited only 10% weight loss, while the natural fibre reinforced composites showed 60% to 80% weight loss [210]. The authors concluded that

upon burial of the composites into the soil, both the water molecules and microorganisms penetrated the polymeric backbone, which eventually degraded the higher cellulose contents of the natural pineapple and coir fibres, resulting in the higher weight losses (%) of the composite materials compared to the pure synthetic materials [210]. The biodegradability of some of the NFRCs reported in the literature is shown in Table 5.

Table 5. Biodegradability of the natural fibre reinforced composites (NFRCs).

NFRCs Composition (wt.%)	Biodegradability Test Conditions	Outcomes	Ref.
Polybutylene succinate (PBS)/Sugarcane rind fibre (SRF) (95:5)	Soil burial test (100 days)	Maximum weight loss (~20%) was found with the PBS/SRF composites than that of pure PBS (~5%).	[211]
Polybutylene adipate-co-terephthalate (PBAT)/Distillers dried grains with soluble (DDGS) (70:30)	Compost (ASTM D5338)	The PBAT/DDGS composite showed higher biodegradability (~98%) compared to the neat PBAT (~92%).	[204]
Polylactic acid (PLA)/Maple wood fibre (70:30)	Compost (ISO-14855)	Acetyl treatment of the maple wood fibres increased their porosity that enhanced the hydrolytic degradation of PLA.	[205]
Polypropylene (PP)/Bamboo (50:50)	Soil burial test (ASTM D5988)	15% biodegradability was observed within 130 days.	[206]
Polyethylene sebacate (PES)/Acylated cellulose fibre (85:15)	Compost (ASTM D5338)	Within 30 days, the biocomposite products showed 100% biodegradability.	[212]
Polylactic acid (PLA)/Kenaf (80:20) and Polylactic acid (PLA)/Rice husk (80:20)	Soil Burial Test (90 days)	The PLA/Kenaf and PLA/Rice husk composites showed 3-times and 2-times higher weight loss (%), respectively compared to the neat PLA.	[213]
Polylactic acid (PLA)/Soy straw (70:30)	Compost (ASTM D5338)	In 60 days, the PLA/Soy straw exhibited 90% degradation while the pure PLA showed 50%.	[214]

6. Challenges Associated with the Biocomposites and Probable Fibre Modifications

The development, production and applications of the plant-based natural fibre reinforced composite materials (NFRCs) are increasing regularly due to their outstanding properties. However, worldwide researchers are facing a number of challenges relating to the development of 100% green biocomposites where both the polymer matrices and reinforcing materials come from natural and renewable resources. Additionally, poor interfacial bonding between the polymer matrix and the reinforcing material, due to the hydrophilic nature of plant-based natural fibres and hydrophobicity of the polymer matrices, is another point of consideration while fabricating the cellulose-based NFRCs [170,215]. Due to the low interfacial interaction, the NFRCs cannot ensure the desired mechanical properties, although they provide the most pursued biodegradability properties, and are significantly cheaper as compared to the high-performance synthetic fibres, such as carbon fibre [170,216]. On top of that, low thermal stability, high moisture absorbency and low wettability of cellulosic natural fibres are some other remarkable challenges in the production of the NFRCs [217]. Moreover, it is not always possible to ensure the similar properties among the natural fibres, as their properties vary based on the changes in weather, season, cultivation conditions and production processing [218,219]. Hence, necessary modifications of the reinforcement fibres must be taken into consideration before processing the improvement of interfacial bonding by enhancing the wettability of the fibres and controlling the moisture absorption of the fibres or matrix [220]. The fibre and polymer matrix

interfacial bonding can be improved by physical and chemical fibre modification techniques. Interfacial bonding between the reinforcement fibres and the polymer matrix can be improved by applying some of the fibre modification techniques—both physical and chemical.

The physical modification of a cellulosic natural fibre refers to the changing of the surface properties such as surface energy, polarity, surface area, cleanliness and wettability. Corona treatment [160,221–223], plasma treatment [224–226], ultraviolet (UV) treatment [227–230], fibre beating [231–233] and heat treatment [234] are some of the remarkable techniques for physical modifications of fibre without hampering the chemical structure of fibres [235–237]. In the case of the corona, for plasma and UV treatment, fibre surface energy is changed using a high voltage at low temperature and atmospheric pressure [160]. Consequently, wettability and fibre–matrix interfacial bonding is improved, which enhances the composite strength. Active surface area is enlarged by the process of fibre beating which allows a good interfacial interaction between fibre and matrix [162]. The heat treatment process removes the non-cellulosic components of plant fibres, such as pectin, lignin and hemicellulose, along with other dirt from the fibres, and allows the cleaned fibre to react with the matrix more actively [238]. The chemical treatment is mostly carried out to deteriorate the inherent hydrophilic nature of the natural fibres, which eventually assists in enhancing the interfacial bonding between the fibres and the matrix [239,240]. Over the past few decades, very intensive research work has continued to better understand the chemical treatment behaviour of cellulosic fibres. Presently, mercerisation [241–245], acetylation [246–249], peroxide treatment [250–252], permanganate treatment [253–257], silanization [258–264], acrylation [265–269], acrylonitrile grafting [270–272] and latex coating [273–275] are the chemical modification techniques most used to improve the reactivity of the natural fibres with the polymeric matrix materials. The hydrophilicity reduction of the cellulosic fibres by eliminating the proportions of hydroxyl groups (–OH) is the ultimate objective of the abovementioned chemical modification techniques [24]. While, due to the reduction in the number of –OH groups, the moisture absorbency of the fibres is reduced, the non-cellulosic components and dirt are removed as the by-products of the chemical reaction, which allows an improved load transfer capacity through the fibre–matrix interface. Figure 6 illustrates the often used chemical modification techniques associated with the cellulosic fibres [276].

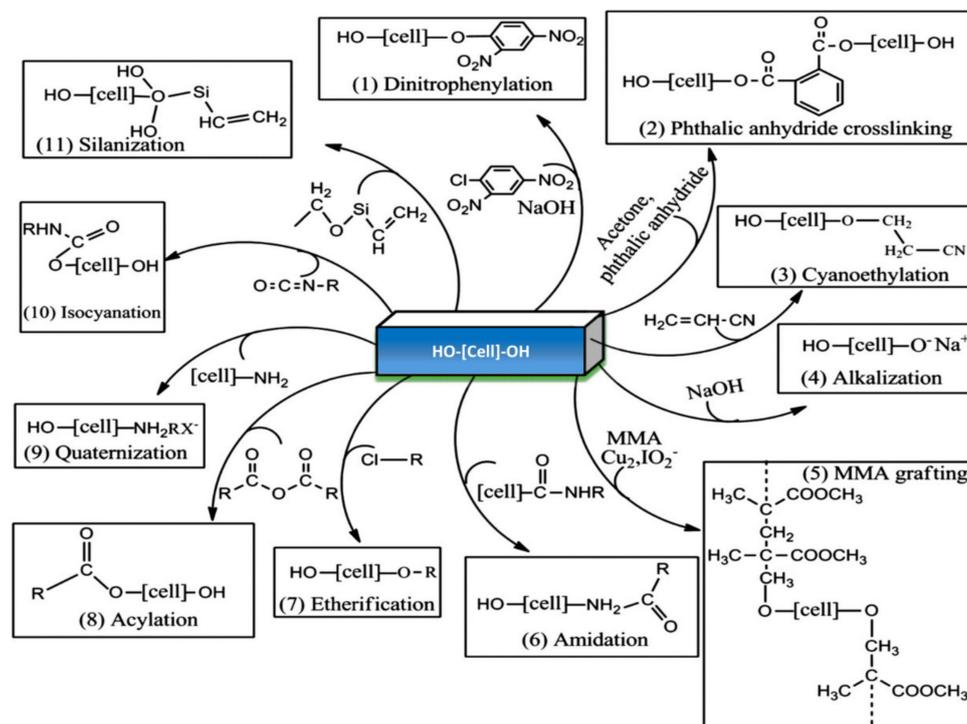


Figure 6. Chemical modifications of the plant-based fibres for biocomposites (Reprinted with permission from [276]; Copyright 2015 Elsevier).

7. Potential Application Areas of Biocomposites

Many countries across the world have imposed restrictions for industries in the use of oil-based raw materials while fabricating different products [277,278]. For example, in the year of 2005, the European Commission (EU) executed “European Guideline 2000/53/EG,” which ensured the utilization of 85% recyclable materials while fabricating the automobile parts [21]. This amount was further augmented to 95% in the year of 2015 [22]. Light weight but greater mechanical strength; lower manufacturing costs; resistance to fatigue and corrosion; and greater availability, renewability and biodegradability than synthetic fibres, are some of the major reasons for this increased demand of NFRCs [279–282]. The potential application areas have been increasing dramatically over the last few decades, including but not limited to the automobile, packaging, military, sports, medical, building and constructions sectors [279–281]. Among these, the applications of NFRCs are the most prevalent in the automobile industry, due to the requirements for eco-friendly lightweight materials and associated costs [9,13,55]. Henry Ford fabricated the first NFRCs using hemp fibres in the year of 1940 [22]. Later, several car manufacturers reported the fabrication of car bodies and other associated parts from NFRCs in the 1950s and in between 1990 and 1996, which gradually increased and gained popularity [13,22], and in recent years from 2014 to 2019, an increase of 11% in production was reported [283].

The natural fibre-based composite market is expected to grow to \$531.3 million US in the year 2019 from \$289.3 million in 2010 with 28% of market shares occupied by natural fibres [283,284]. Table 6 shows the main producers and the annual production of some plant-based natural fibres commonly used in NFRCs.

Table 6. Producers and annual production of most widely used plant-based natural fibres [56–60].

Fibre	Producer	Production Amount ($\times 10^3$ ton)	Price (US\$/ton) ^a
Abaca	Philippines (85%), Ecuador	70	345
Bagasse	Brazil, China, India, Thailand, Australia, USA	75,000	3.5–11.8 (7.65)
Coir	India, Sri Lanka, Thailand, Vietnam, Philippines, Indonesia, Brazil	1200	200–500 (350)
Cotton	China, Brazil, India, Pakistan, USA, Uzbekistan, Turkey	25,000	1500–4200 (2850)
Flax	France, Belgium, Netherland, Poland, Russian Federation, China	830	2100–4200 (3150)
Jute	India (60%), Bangladesh, Myanmar, Nepal	3450	400–1500 (950)
Kapok	Philippine, Malaysia, China, South America, Indonesia, Thailand	101	-
Kenaf	India (45%), China, Malaysia, USA, Mexico, Thailand, Vietnam	970	300–500 (400)
Bamboo	China, Japan, India, Chile, Ecuador, Indonesia, Myanmar, Nigeria, Sri Lanka, Philippines, Pakistan	30,000	500
Hemp	China (80%), Chile, France, Germany, UK	214	1000–2100 (1550)
Ramie	China, Brazil, Lao PDR, Philippines, India	280	2000
Sisal	Brazil (40%), Kenya, Tanzania, China, Cuba, Haiti, Madagascar, Mexico, Sri Lanka, India	378	600–700 (650)
Banana	India (22%), China, Philippines, Ecuador and Brazil	134,000	890
Pineapple	Costa Rica, Philippines, Taiwan, Brazil, Hawaii, India, Indonesia	1318	360–550 (455)

Note: ^a is the average price of fibres.

It has been reported that application of NFRCs would result in the reduction of nearly 20% of manufacturing costs and 30% of automobile weight which would also help in reducing the fuel consumption [9,55]. The European car manufacturers are making serious attempts at incorporating the NFRCs in various portions of cars, such as car seats, backrests, front and back door liners and in door-trim panels [285]. The German car manufacturers are currently focusing on the fabrication of

exterior body parts for cars and trucks with bio-based composites [25,55,286]. It has been reported that in the year of 2004 the BMW group used 10 kilotonnes of renewable natural fibres while producing the NFRCs for their cars [287]. Table 7 shows the utilisation of different plant-based natural fibres in various parts of the automobiles [9,55,288–291]. It has been reported that in the year of 2012, the European automobile industry has used 38% wood, 25% cotton, 19% flax, 8% kenaf, 5% hemp and 7% other natural fibres such as jute, coir, sisal and abaca to fabricate the natural fibre reinforced composites (NFRCs) to use in this particular industry [290]. Hence, it can be predicted that in near future the NFRCs would be used in a higher proportion in the automobile industry.

Table 7. Applications of the plant-based natural fibre reinforced composites (NFRCs) in the automobile industry [9,55,288–291].

Car Manufacturer	Model	Application Areas
Rover	2000 and others	Insulations, rear storage panel
Audi	A2, A3, A4, A6, A8	Seatback, side and back door panel, spare-tire lining, boot-liner
Opel	Astra, Vectra, Zafira	Head-liner panel, door panels, instrumental panel
BMW	3, 5 and 7 series	Head-liner panel, seatback, door panel, car dashboard
Toyota	Raum, Harrier, Brevis	Floor mats, door panels, spare tire cover
Mercedes Benz	C, S, E and A classes	Door panel, glove box, seat backrest panel, trunk panel, sun visor, roof cover
Volkswagen	Bora, Golf, A4	Door panel, seatback, boot-liner
Peugeot	406	Parcel shelf, seatback, door panels
Fiat	Brava, Punto, Marea	Door panels
Volvo	V70, C70	Cargo floor tray, seat padding
Ford	Focus	Floor trays, door inserts, door panels, boot-liner
Mitsubishi	-	Door panels, instrumental panels
Citroen	C5	Interior door panelling
Renault	Twingo, Cilo	Rear parcel shelf

In addition to the automobile industry, the biocomposites fabricated from the cellulosic natural fibres are extensively used in geotextiles, medicine, sports, construction and packaging (Table 8). After the automobile industry, the building and construction industries are the second-largest consumers of NFRCs owing to the demand for the eco-friendly green buildings, and load-bearing and non-load bearing capabilities of NFRCs [292,293]. Roofs, windows, panels and doors are built using the NFRCs [293]; for example, the composites fabricated from sisal fibres can be used in producing tanks, pipes and even roofing materials that could replace asbestos [294,295].

Table 8. Applications of cellulosic fibres in different industries [296–299].

Fibres	Industrial Applications
Hemp	Textiles, geotextiles, paper and packaging, electrical, furniture, cordage, construction items, producing banknotes and manufacturing pipes
Kenaf	Mobile cases, insulation materials, animal bedding and packaging materials
Coir	Building panels, storage tanks, helmets and post-boxes, mirror casing, paperweights, mats and seat cushions
Cotton	Textiles, cordage, furniture upholstery and goods
Jute	Building panels, door frames, chipboards, geotextiles, door shutters, packaging, transport and roofing sheets
Wood	Window frames, fencing and panels
Ramie	Packing materials, industrial sewing threads, fishing nets, canvas and paper manufacturing
Sisal	Panels, doors, paper and pulp
Stalk	Bricks, pipes and building panels
Bagasse	Decking, railing system and fencing
Rice husk	Window frames, doors, panels, decking and fencing
Oil palm	Building and construction materials
Flax	Tennis racket, bicycle frames, snowboarding, panels, doors, laptop cases

8. Conclusions

Plant-based natural fibre reinforced composites (NFRCs) have some excellent properties, such as biodegradability, biocompatibility and renewability. Hence, it is more appropriate to use the NFRCs instead of the petroleum-based synthetic materials, which are neither eco-friendly nor obtained from the renewable sources. This review thoroughly illustrated the required properties of the cellulosic fibres and the polymeric matrices for the fabrication of the NFRCs. Additionally, the mechanical properties, challenges and potential application areas of the NFRCs have been discussed. Although it is evident that the plant fibres are not free from some drawbacks, such as possessing higher moisture retention, these can be overcome by applying various physical and chemical modifications. Moreover, it is difficult to produce 100% green biocomposites wherein both the polymeric matrix and the reinforcing material are derived from the natural and renewable sources. Therefore, more focus is required to commercially develop pure green biocomposites to support sustainability. It is necessary to find new sources of natural biopolymers and fibres which can be used as both the polymer matrices and the reinforcing materials. Research also needs to find how can we utilize the abundantly available short and non-spinnable natural fibre wastes, either as reinforcing materials or as polymer matrices to fabricate fully green biocomposites.

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Abbreviations

NFRCs	Natural Fibre Reinforced Composites
PLA	Polylactic Acid
PE	Polyethylene
PP	Polypropylene
PAN	Polyacrylonitrile
PC	Polycarbonates
RTM	Resin Transfer Moulding
UD	Unidirectional
PF	Palm fibre
PBS	Polybutylene succinate
PBAT	Polybutylene adipate-co-terephthalate
PES	Polyethylene sebacate
PS	Polystyrene
PMMA	Polymethyl methacrylate
PVC	Polyvinyl chloride
PVA	Polyvinyl acetate
PET	Polyethylene terephthalate
RFI	Resin Film Infusion
VaRTM	Vacuum-assisted resin transfer moulding
CP	Cross ply
PHA	Polyhydroxyalkanoate
SRF	Sugarcane rind fibre
DDGS	Distillers dried grains with soluble

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