1

Natural and Synthetic Fibers for Hybrid Composites

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1.1 Introduction

Emerging research concerns mainly with the environmental and economic issues related to the design of new materials for future industries. For the past few decades, various industrial sectors are trying to replace the synthetic fibers with natural fibers as reinforcements in polymer composites. Composite materials have been providing a major amount of research and industrial work for an age because of their favorable and outstanding properties. Moreover, they can be produced and processed with low investment [1]. The composite material is a combination of fiber/filler and matrix (polymer). The combination of fiber and matrix can be arranged by using the hybrid (one or two fibers) with the base polymer matrix. The main purpose of using fibers is to provide strength to the composite. Factors that influence the properties of fibers are length, orientation, shape, and materials [2]. Based on the polymer used for the manufacturing, fibers can be selected either naturally or synthetically. Fibers that are generally obtained from plant, animal, or cultivated are called natural fibers such as jute, ramie, sisal, hemp, coir, grewia optiva, silk, bamboo, etc. On the other hand, fibers that are manufactured through various man-made processes are called synthetic fibers such as carbon, Kevlar, glass, etc. Both natural and synthetic fibers have their own merits and demerits with respect to the polymer used for the fabrication of the composite. As compared to synthetic fibers, natural fibers are environment friendly, renewable, cheap, nonhazardous, nonabrasive, and easily available, but the cons of using natural fibers is their low mechanical properties as compared to synthetic fibers [3]. Another major drawback of natural fibers is their affection toward water because of the presence of cellulose. This hydrophilic nature leads to poor interfacial bonding between the fiber and matrix. On the other hand, synthetic fibers, being hydrophobic materials, form a good bonding with the polymers. Sometimes, fibers are applied in hybrid form to take the advantage of both

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natural and synthetic fibers, which is generally called hybridization in composite. This hybridization brings out various attractive properties of both natural and synthetic fibers, which resulted in superior mechanical and tribological properties of the final composite [4, 5]. However, this is not the sole cause of the variation in the properties of the composite. Fiber type, fiber size, percentage of fiber, polymer used, processing techniques, and chemical treatment are the vital factors that can be employed to achieve promising results in the composite properties. The present discussion is therefore relied on the various natural and synthetic fibers available, their effect on the composite, chemical alteration of natural fibers, and the applications of natural and synthetic fibers. The discussion also includes the inclusion of hybridization in composite structure and their effects.

1.2 Natural Fibers

The suitability of synthetic fibers in polymer composites is losing hold because of their higher price, nonbiodegradability, and problems of dumping off. These problems can be easily resolved with the exploitation of natural fibers in the field of polymer composites, but a compromise is made among the physical and mechanical properties obtained.

Natural fibers, as the name suggests, are a particular substance that exist naturally and are not man-made. Being renewable, natural fibers are assumed as a good substitute for traditional materials. Because of their higher aspect ratio and high strength, natural fibers are gaining greater attention in the automotive sectors for structural applications [6]. In addition, natural fibers are also gaining interest in the field of textile, medical implantation, building structures, aviation, etc. New plant fibers are being investigated by researchers seeking their interest in developing lightweight, renewable, economical, and socially benefited for replacing traditional materials. It has been found that composites are produced by using natural fibers that hold good electrical resistance, better mechanical properties,

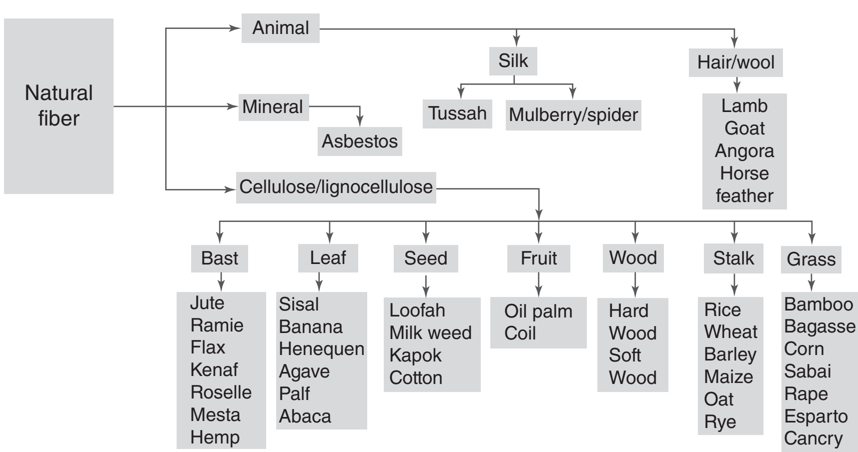


Figure 1.1 Classification of natural fibers [12, 13].

decent thermal and acoustic insulating properties, and higher resistance to fracture in some cases [7–9]. Fibers can be transformed into various forms, such as rovings, mats, fabrics, and yarns, and then used as reinforcements in composite materials. [10, 11]. Natural fibers are available in three forms: vegetables/plants, animals, and minerals (e.g. asbestos), as shown in Figure 1.1 [12, 13].

The physical and mechanical properties of natural fibers are not as attractive as those of synthetic fibers. However, if we compare these properties, it can be well stated that synthetic fibers can be replaced for some but not all areas of the polymer composites. These areas can be interiors of automobile, dashboard, rooftops, tiles, etc., where the load bearing requirement is low. Some common natural fibers and synthetic fibers and their properties are listed in Table 1.1.

1.3 Microstructure of Natural Fibers

Natural fibers consist of a complex structure having amorphous lignin as the reinforced material and/or hemicelluloses as the matrix. Natural fibers generally have cellulose, lignin, hemicelluloses, pectin, water-soluble compounds, and wax constituents beside cotton. Lignin, hemicellulose, and pectin jointly function as matrix and adhesive to hold the cellulosic frame structure of natural fibers [14]. The properties of cellulose, lignin, hemicellulose, and pectin are discussed in Table 1.2 [15] (Table 1.3).

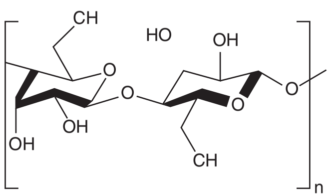
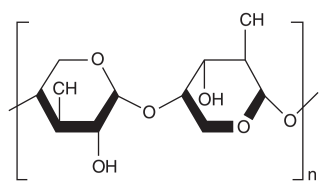
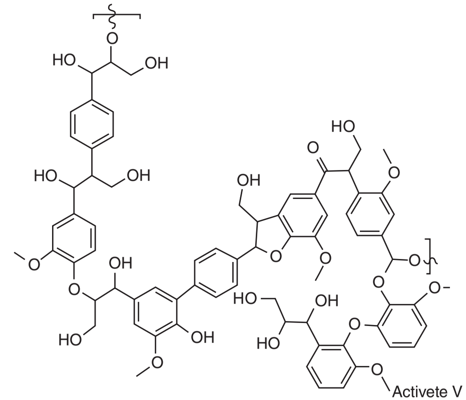
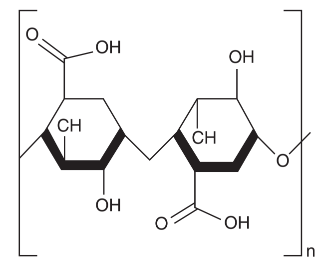
1.4 Natural Fiber-Reinforced Polymer Composites

Composites are the combination of two or more constituents having different phases, and phases can clearly be observed macroscopically by naked eyes. Composites have two main parts: one is matrix and another is reinforcement. Matrix has constant properties throughout the section and is ductile in nature. Therefore, another phase is added in the matrix to enhance the property in the desired direction is known as reinforcement. Matrix provides the support and texture and reinforcement provides strength for matrix. According to the materials used, matrix is of three types, namely, polymers, metal matrix, and ceramic metal composites. Polymers are the best option to be used in various industries because they show convenience in processing, increased productivity, and reduced cost [3]. A natural fiber-reinforced polymer (NFRP) is a composite material that consists of a polymer matrix embedded with high-strength fibers, such as jute, cotton silk hemp wool, etc. Upcoming biopolymers entail special processing settings for the enhancement of specific properties. PLA (polylactic acid), PHAs (polyhydroxyalkanoates), PHB (polyhydroxybutyrate), PBS (polybutylene succinate), TPSs (thermoplastic starches), and PEF (polyethylene furanoate) are common trending biopolymers in the composite field. Among all the biopolymers, PLA is found to be more economic and available [16]. The properties of the composites not only depend on the percentage, orientation, and shape of fiber but also majorly depend on the interfacial/surface bonding

Table 1.1 Properties of natural fibers in relation to those of synthetic fibers [51–53].

Fiber	Density (g/cm^3)	Length (mm)	Diameter (μm)	Failure strain (%)	Tensile strength (MPa)	Young's modulus (GPa)	Specific tensile strength (MPa/(g cm^3))	Specific Young's modulus (GPa/(g cm^3))
Ramie	1.5	900–1200	25–50	2.0–3.8	400–938	44–128	270–620	29–85
Silk	1.3	Continuous	10–13	15–60	100–1500	5–25	100–1500	4–20
Cotton	1.5–1.6	10–60	11–22	3.0–10	287–800	5.5–13	190–530	3.7–8.4
Pineapple leaf fiber	1.07	3–9	100–280	2.2	120–130	4.405	112.15–121.5	0.68–2.04
Flax	1.5	5–900	12–16	1.2–2.2	345–1830	27–80	230–1220	18–53
Hemp	1.4–1.5	5–55	16–50	1.6	550–1110	58–70	370–740	39–47
Jute	1.3–1.5	1.5–120	17–20	1.5–1.8	393–800	10–55	300–610	7.1–39
Harakeke	1.3	4–5	6–30	4.2–5.8	440–990	14–33	338–761	11–25
Sisal	1.33–1.5	900–1000	200–400	2.0–2.5	507–855	9.4–28	362–610	6.7–20
Alfa	1.4	350	—	15	300–900	18–25	214–643	13–18
Coir	1.15–1.46	20–150	10–460	15–30	131–200	4–6	110–180	3.3–5
Oil palm	0.7–1.55	248	50–500	3–4	200–250	3.20	129–357	2.06–4.57
Abaca	1.5	1800–3700	40	1.0–7.0	100–900	6–32	70–600	4–21.3
Bagasse	1.25	1.2	15	1.1	170–290	17–28	136–232	13.6–22.4
Bamboo	0.6–1.1	1–5	14–27	1–3	450–800	5–25	409–1333	4.54–42
Banana	0.91	2.5–13	80–250	1.4–2.9	53.7	3–15	59.01	3–16
Curaua	1.3–1.5	150–1500	40–320	3.7–4.3	500–1150	63.7	333.33–885	7.87–9.08
Date palm	0.9–1.2	20–250	100–1000	2.5–5.4	393–773	13–26.5	327.5–858.89	10.83–29.44
Isora	1.39	6–14	10–20	5, 6	550	—	395.68	—
Kenaf	0.6–1.5	3000	20–80	1, 2	400–800	12	266.67–1333.33	8–20
Piassava	1.40	134–143	400–2400	5–10	138.5	—	98.9	—
E glass	2.5	Continuous	0.55–0.77	2.5	2000–3000	70	800–1400	29
Carbon	1.65–1.75	Continuous	5–10	1.7	3790	—	2165–2400	—
Kevlar-49	1.467	Continuous	12	2.8	2900–3620	151.7	1977–2468	103.4

Table 1.2 Properties of natural fibers.

Cellulose	Hemicellulose	Lignin	Pectin
1. Linear glucose polymer consisting of β-1,4 linked glucose units 2. Produces stable hydrophobic polymers with high tensile strength	1. Branched polymers containing sugar and carbon of varied chemical structure	1. Amorphous, cross-linked polymer network 2. Works as chemical adhesive within and between fibers	1. Complex polysaccharides with chains consisting of glucuronic acid polymers and residue of rhamnose. 2. Calcium ions improve surface integrity in pectin rich area
			

Source: From Westman et al. 2010 [15].

Table 1.3 Chemical composition of natural plant fibers.

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Wax (wt%)	Pectin (wt%)
Cotton	82.7	5.7	—	0.6	—
Ramie	68.6–76.2	131–16.7	0.6–0.7	0.3	1.9
Bagasse	55.2	16.8	25.3	—	—
Henequen	77.6	4–8	13.1	—	—
Bamboo	26–43	30	21–31	—	—
Flax	71	18.6–20.6	2.2	1.5	2.3
Kenaf	72	20.3	9	—	—
Jute	61–71	14–20	12–13	0.5	0.4
Hemp	68	15	10	0.8	0.9
Ramie	68.6–76.2	13–16	0.6–0.7	0.3	0.3
Pine apple leaf fiber (PALF)	70–82	—	5–12	—	—
Abaca	56–63	20–25	7–9	3	12, 13
Sisal	65	12	9.9	2	10
Coir	32–43	0.15–0.25	40–50	—	3, 4
Oil palm	65	—	29	—	—
Pineapple	81	—	12.7	—	—
Curaua	73.6	9.9	7.5	—	—
Wheat straw	38–45	15–31	12–20	—	—
Rice husk	35–45	19–25	20	14–17	—
Rice straw	41–57	23	8–19	8–28	—
Banana	81.80	—	15	—	—
Date palm	40.21	12.8	32.2	5.08	—
Kapok	64	23	13	—	—
Areca	—	35–64.8	13–24.8	—	—

between the fiber and the matrix. Subsequently, better interfacial bonding leads to greater bonding between the fiber and the matrix. Thus, surface treatment of fiber is considered as a vital process in the field of composites. Chemical treatment has now become one among the most important areas in today's research. A large amount of literature available has targeted the studies on the treatment of fibers to improve the bonding between fiber and matrix [17]. It was reported in the study that treatment of fibers with alkali solution (20% NaOH solution) leads to reduction in moisture absorption to 20%, provided the fiber is further treated with 5% acrylic solution [18]. Literature also suggested that reinforcement of fiber should be limited to a certain amount beyond that limit and no changes have been observed. Properties such as tensile strength, young modulus, flexural strength, and impact strength are found to be enhanced with the reinforcement of fiber. Alongside, natural fillers are also available in the market, which not only enhance the mechanical properties but also make the composite economical viable. Fillers have the ability to improve properties such as toughness and fatigue. With regard to fillers, natural fillers obtained from processing of oak wood enhanced strain in failure for a wood filler polypropylene composite but reduce the strength and stiffness as compared to a virgin polymer produced in a six-step filter process [19]. Variation of percentage of fiber indeed is a vital factor in the properties of a composite. The presence of cellulose and hemicellulose in the natural filler provides better adhesive property upon treatment with NaOH. This may be attributed to the porosity created at the surface of the fiber because of the addition of bamboo fillers to the epoxy–fiber composite. Carada et al. [20] investigated the heat treatment of kenaf fiber. It was performed for an hour at different temperatures ranging from 140 to 200 °C with the difference of 20 °C. Results obtained in the study suggested that adequate tensile strength was obtained at 140°, and no improvement is observed beyond it [20]. The fiber in mat form also improves the mechanical property of the polymer composite. Hemp fiber in the form of mat after treatment resulted in enhanced mechanical property of the hemp–polyester composite [21]. Alkali treatment of bamboo fiber leads to enhancement of interfacial bonding of fiber and matrix [22]. One of the treatments called biological treatment of fiber resulted in the improvement of tensile strength of the composite and reduces the degradation of sample [23].

1.4.1 Synthetic Fibers

Synthetic fibers are the man-made fibers that do not originate naturally. Products of petroleum are the main source of synthetic fibers. Synthetic fibers have better properties than natural fibers. Different chemicals having their own property are mainly used to produce the synthetic fibers. Nylon, acrylics, polyesters, polyurethanes, etc., are the synthetic fibers produced from chemical products [24]. These fibers possess high mechanical property, durability, and stability and have long-lasting life span. There are various types of synthetic fibers in which mainly three types of synthetic fibers are used in the composite industry at a large scale: Kevlar (aramid), glass fiber, and carbon (Figure 1.2).

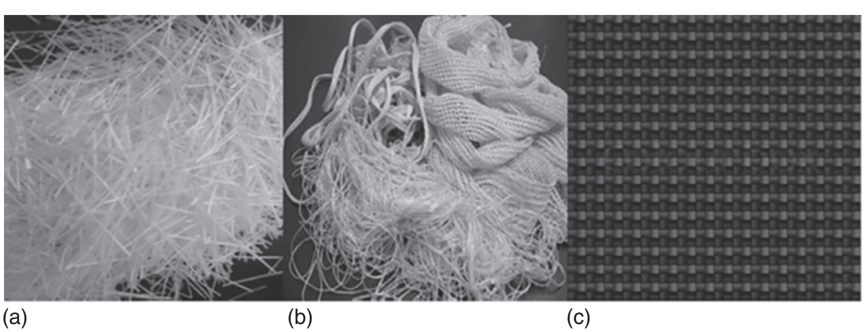


Figure 1.2 Images of synthetic fibers: (a) glass fiber, (b) Kevlar fiber, and (c) carbon fiber.

Table 1.4 Different types of glass fibers and physical and mechanical properties.

Glass fiber type	Silicon dioxides (SiO_2) (%)	Density (g/cm^3)	Tensile strength (MPa)	Modulus (GPa)	Elongation at break (%)
A-type	63–72	2.44	3300	72	4.8
C-type	64–68	2.56	3300	69	4.8
D-type	72–75	2.11	2500	55	4.5
E-type	52–56	2.54	3448	72	4.7
R-type	56–60	2.52	4400	86	5.1
S-type	64–66	2.53	4600	89	5.2
ECR-type	54–62	2.72	3400	80	4.3
AR-type	55–75	2.7	1700	72	2.3

Source: From Saba and Jawaid 2017 [24].

1.4.2 Glass Fibers

Highly attractive physical and mechanical properties of glass fibers, ease of manufacturing, and their comparable low cost to carbon fibers make it a highly preferable material in high-performance composite applications. Glass fibers are composed of oxides of silica. Glass fibers have outstanding mechanical properties, such as less fragility, extreme strength, less stiffness, and lightweight. Glass fiber-reinforcing polymers consist of a large family of different forms of glass fibers such as longitudinal, chopped strand fiber, woven mat, and chopped strand mat used to increase the mechanical and tribological properties of polymer composites [25]. Study has been carried out to investigate the suitability of glass fibers with the polymer such as rubber. It is possible to obtain high initial aspect ratio with fibers of glass, but fragility causes fibers to break during processing. Some physical and mechanical properties of glass fibers are listed below (Table 1.4).

1.4.3 Carbon Fibers

It is one of the strongest fibers known and has wide applications in high-performance applications. Because of its outstanding mechanical and thermal properties such as high stiffness, high thermal conductivity, high tensile strength, high elastic modulus, low weight, high temperature tolerance, high chemical resistance, and low weight, they are mainly used in the aerospace industry. Carbon fibers are manufactured from rayon, petroleum pitch, and polyacrylonitrile (PAN) [26]. There are three types of fore runners commonly used such as PAN forerunner, rayon forerunner, and pitch forerunner. Fifty percent of fiber mass of commercial carbon fibers are mainly generated by PAN forerunner. Short carbon fibers are extensively used because of their appealing properties such as ease of fabrication, high stiffness, relatively low cost, and strength to weight ratio [27] (Table 1.5).

Table 1.5 Properties of carbon fibers.

Property	Precursor		
	PAN	Pitch	Rayon
Density (g/cm^3)	1.77–1.96	2.0–2.2	1.7
Tensile strength (MPa)	1925–6200	2275–4060	2070–2760
Tensile modulus (GPa)	230–595	170–980	415–550
Elongation (%)	0.4–1.2	0.25–0.7	—
Thermal conductivity (W/m K)	20–80	400–1100	—
Fiber diameter (μm)	5–8	10–11	6.5

Table 1.6 Typical properties of Kevlar fibers.

Property (unit) / Kevlar grade	Density (g/cm^3)	Diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)
Kevlar 29	1.44	12	2760	62	3.4
Kevlar 49	1.44	12	3620	124	2.8

1.4.4 Kevlar or Aramid Fibers

Kevlar fibers or aromatic polyamide threads (aramid) are produced by using *para*-phenylenediamine and terephthaloyl chloride [28]. Because of the molecular orientation, these fibers have high strength and excellent thermal conductivity as compared to glass and carbon fibers [29]. The manufacturing process and the equipment used in the manufacturing of Kevlar fibers are very costly, so Kevlar fibers are generally high in cost [29]. Kevlar fibers have abundant properties such as good resistance to abrasion, nonconductivity, high degradation temperature, good fabric integrity, good resistance to organic solvent, no melting point, and low flammability [30]. There are three types of Kevlar fibers in existence: Kevlar, Kevlar 49, and Kevlar 29 (Table 1.6).

In order to increase the mechanical properties and improve the interfacial interaction, some modifications were adopted, such as direct hydrolysis, planetary ball milling, and hydrolysis treatment of ball mill [31]. Various kevlar fiber (KF) treatment methods are as follows (Table 1.7).

1.4.5 Comparison Between Natural and Synthetic Fibers

The selection of natural fibers depends on the availability in local level and after that is seeking to property requirements. It is seen that the mechanical properties of natural fibers are moderate as compared to those of synthetic fibers; similarly, in opposite manner, the thermal and moisture sensitivity of natural fibers is higher than that of the synthetic fibers. Natural fibers exhibit superior mechanical properties such as flexibility, stiffness, and modulus compared to glass fibers. In

Table 1.7 Nomenclature used for Kevlar fibers without and with various surface treatments [31, 54].

Fiber	Surface modification techniques
Kevlar	Untreated
	Hydrolyzation
	Ball milling technic
	Ball milling + hydrolyzation
	Ball milling + phosphoric acid
	Ball milling + phosphoric acid + hydrolyzation

Table 1.8 The basic comparison between natural and synthetic fibers.

Properties	Natural fibers	Synthetic fibers
Density	Low	Twice that of natural fibers
Cost	Low	High, compared to natural fiber (NF)
Renewability	Yes	No
Recyclability	Yes	No
Energy consumption	Low	High
Distribution	Wide	Wide
CO_2 neutral	Yes	No
Abrasion to machines	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Not biodegradable

an environmental point of view, the major factor of selection of natural fibers to the synthetic fibers is that recyclability of natural fibers is better than the synthetic fibers. Some basic comparison between natural and synthetic fibers is shown in Table 1.8 [32].

1.5 Hybrid Fiber-Based Polymer Composites

Hybridization is a technique in which two or more than two fibers are employed to a single-base matrix. The term hybridization sometimes also refers to the implementation of fillers in the fiber polymer composite [33]. Hybridization is not new to the researchers; in fact, it has been in practice for centuries. Properties such as physical, mechanical, and thermal get influenced in a positive manner because of the hybridization. This is attributed to the increase in the fiber–fiber and fiber–matrix adhesion. To reduce the overall cost of manufacturing, natural fibers are added to synthetic fiber polymer composites but compromising with the strength of the composite. It has been found that the hybridization has been in the top most priorities of various researchers. Hybrid composites are now being formed in various forms. These are core shell type, sandwich type, laminated type, two-by-two type, intimately type, etc.

Mechanical, thermal, and dynamic properties increase substantially for oil palm–epoxy-based composite because of the enhancement in the adhesive bonding of fiber and matrix. Addition of natural fibers in glass fiber-reinforced polymer composites leads to enhancement of impact tensile and flexural strength [34]. It has been noticed that hybridization of jute and oil palm fiber resulted in higher tensile strength, provided that the weightage of jute fiber should be higher [35]. The majority of work in the field of hybridization has been stick to hybridization of natural and synthetic fibers. In this regard, sisal, a natural fiber, can be hybridized with glass fibers, which results in the enhancement of tensile and flexural modulus. Hybridization does not always work for every aspect of the composite taken into consideration. It can be stated that enhancement of one property sometimes leads to reduction of another and vice versa. Similar results have been reported for sisal–glass/polypropylene hybridization. It has been reported that tensile and flexural strength increases but negotiating with the properties such as tensile and flexural modulus. Moreover, thermal and water resistance behavior also improves for sisal–glass polymer composites [36]. Hemp, which is a plant fiber, is also finding its place in hybridization because of its influential properties. In the hybrid composites, layering sequence plays an important role in deciding the mechanical properties of the formed composites. From previous research, it is concluded that hybrid laminates with two extremes synthetic fibers plies on both sides has the optimum amalgamation with a good balance between the properties and the cost. It has also been found that glass fibers, when hybridized with hemp fiber, lead to improvement in mechanical and physical properties and reduction in the overall cost of composites [37]. Similar to hemp, flax fiber well known from the centuries can also be hybridized with synthetic fibers [38]. Hybrid composites of flax and glass fiber lead to significance improvement in the tensile strength of the composite. Jute is a natural fiber available in very large amount, which is also applied in the hybridization with glass leading to better tensile and flexural strength of the composite. Hybridization also plays a very critical role in the enhancement of properties for green composites [39]. Thus, green composites of bamboo–cellulosic fiber-based PLA composite are found to have better resistance for fracture toughness [40].

1.5.1 Applications

Applications of synthetic fiber polymer composites can be seen as gradual increasing phenomena.

It is the need of the hour that requires replacement of synthetic fibers with the natural fibers for various applications because of the favorable properties of natural fibers [41, 42]. However, because of certain drawbacks, the natural fibers cannot be used solely; hence, the time requires the combined advantages of both fibers (natural and synthetic) in a single component. This gives rise to the development of hybrid composites; the various applications of hybrid natural fiber composites are as follows:

Parts of automobile such as door panels, instrument panels, armrests, headrests, and seat shells and parcel shells are now being fabricated by hybrid fiber composites [43]. In the recent development, the under-floor protection chamber in a passenger car for the safety purpose has been successfully designed and developed by the banana fiber polymer composite [44]. Similarly, mirrors, visor of a two-wheeler, billion seat cover, indicator cover, cover L-side, and name plate are also being manufactured with the use of natural sisal fiber polymer composites [45]. Cost-effective components can also be easily manufactured with the use of hybridization technique [46]. One such application can be seen in the application of bumper of automobile, which is manufactured by the hybridization of kenaf and glass fibers [47]. In the water bodies such as small boats and ships, composites based on glass–sugar palm fiber finds hell of a lot of applications [48]. Natural fiber and synthetic fiber-based composites have proved their potential to be a good material for the structural applications. Jute fiber-based hybrid composites with concrete as a matrix are being developed for the application of structural composites [49]. These applications comprise building panels, roofing sheets, door frames, door shutters, transport, packaging, geo textiles, chipboards, absorbent cotton, storage device, furniture, transportation, household accessories, and biodegradable shopping bag. Coir-based polymers and ceramic composites are also used in building panels, flush door shutters, roofing sheets, storage tank, packing material, helmets and postboxes, mirror casing, paper weights, projector cover, voltage stabilizer cover, a filling material for the seat upholstery, brushes and brooms, ropes and yarns for nets, bags, and mats, as well as padding for mattresses and seat cushions. Thermally sound materials that require fire resistance properties can also be fabricated with the help of natural fiber polymer composites. This is due to the fact that natural fibers have porous microstructures that provide fire-resistant properties [50].

1.6 Conclusion

Advancement in material research has been pushed ahead further by the development in composite materials. Diversion of research from monolithic materials to polymeric composites has been successfully achieved by natural and synthetic polymeric composites. High-strength materials can now be easily designed and manufactured by the use of composite materials. Synthetic fiber-reinforced composites are somehow shown to be a better alternative for metal materials as compared to natural fiber-reinforced composites, but sustainability issues make the natural fiber more impressive. Chemical modification of natural fiber helps in enhancement of strength of natural fiber and interfacial bonding between the fiber and the matrix. Fabrication technique is also an important issue that should also be taken in the consideration. Research should be excelled in the field of hybridization to achieve better and sustainable composites.

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