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Production, Properties, and Applications of Fiber-Reinforced Polymer Composites

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Abstract: Among the materials accessible this century, composites have shown the greatest promise and discrimination. The market is seeing a rise in the significance of lightweight materials with high strength for certain applications, which is driving the use of composites reinforced with fibers of synthetic or natural materials. Fiber-reinforced polymer composites have remarkable qualities such a high strength-to-weight ratio, high durability, stiffness, damping property, flexural strength, and resistance to corrosion, wear, impact, and fire, among many others. Many different industrial sectors have found uses for composite materials due to their vast variety of various properties, including mechanical, construction, aerospace, car, biomedical, and marine. Because the performance of composites is largely dependent on the elements that make them up and the processes used to make them, research into the functional properties of different types of fibers, how they are classified, and the manufacturing techniques used to make composites is necessary to determine which material properties are best suited for a given application. In order to choose the best fiber-reinforced composite material for important uses, this article provides a general outline of different types of fibers, how they work, what they are classified as, and the several ways that fiber composites are made. As an alternative to individual metals or alloys, fiber-reinforced composites have shown great promise due to their outstanding performance in a wide variety of industries.

Keywords: fiber-reinforced polymer; composite materials; natural fibers; synthetic fibers

1. Introduction

The need to enhance materials in terms of durability, affordability, density, and strength has arisen as a result of the fast expansion of industrial sectors. One material with improved qualities that might be useful in many different contexts is composite material [1-4]. Two or more materials, often in particle or fiber form, are combined to produce a composite. One of these components is found in the matrix phase. Composites made from either natural or synthetic fibers have found widespread use in several industries, including building and mechanical engineering, transportation, biomedicine, and the maritime sector [5-8]. The structural, mechanical, and tribological characteristics of fiber-reinforced composite (FRC) material are significantly improved compared to many traditional materials, which is why composites have been proposed as an alternative in recent research investigations [9–11]. Composites did improve the material's durability, but there's now serious worry about the buildup of plastic trash in the environment [12]. Environmentally friendly materials linked to cleaner production methods have been developed by researchers worldwide in response to this issue [13–15]. The hundreds of tons of composite trash produced annually necessitated the development of many composite recycling techniques. One method of mechanical recycling is pulverization, which uses the reduced particle size of recyclates as a filler in sheet molding compounds. Composite trash may be thermally recycled by pyrolysis or by burning composite materials with a high calorific value, which produces a tremendous quantity of heat energy. Methods like high-voltage fragmentation and chemical recycling, sometimes known as solvolysis, are more efficient. Green composites have better material qualities and less residue buildup thanks to natural fillers such fibers, cellulose nanocrystals, and nanofibrillated cellulose added to a polymer matrix [16–19]. A number of studies have highlighted the benefits of using cellulosic fibers in composites. These include the fact that they are naturally occurring, non-toxic, renewable, inexpensive, and capable of bonding with a cement-based matrix to significantly improve a material's ductility, toughness, flexural capacity, and impact resistance, among other properties [20-22]. Composites are reinforced using current methods by adding mineral additives such as fly ash, limestone powder, brick powder, and many more. Fly ash, when added to concrete composites for structural purposes, increases fracture toughness and, therefore, the material's lifetime [23,24]. The three primary types of natural fibers are those derived from plants, animals, and minerals. Fibers derived from plants offer several advantages over their mineral-based counterparts, including lower costs, biodegradability, availability, and excellent physical and mechanical properties, as well as a lack of asbestos, which makes them less attractive for use in fiber-reinforced composite materials [25,26]. Plant fibers include leaf fibers (sisal and abaca), bast fibers (flax, jute, hemp, ramie, and kenaf), grass and reed fibers (rice husk), core fibers (hemp, jute, and kenaf), seed fibers (cotton, kapok, and coir), and all other types, which may include wood and roots. Polyester, polypropylene (PP), polyethylene (PE), and epoxy are examples of synthetic polymer matrices that are derived from petrochemicals [27]. Natural polymer matrices also exist.

The most recent findings aid in the creation of hybrid composites that include both synthetic and natural fibers. The composite structures consisting of more than one type of fiber are defined as hybrid composites. As an example, one way to combine these fibers is to stack them on top of each other. Another is to mix different types of fibers in the same layer to create an interplay hybrid. Still another is to selectively place fibers where they are needed for better force, and yet another is to place each fiber according to its specific orientation [28]. While stacking fibers is the simplest method, the others make it more difficult to get a desirable hybridization result. Many researchers got success by developing optimized composite materials for efficient use in particular applications by varying fiber content, its orientation, size, or manufacturing processes. To make good use of FRCs, one must be familiar with their mechanical, electrical, thermal, and physical characteristics. FRCs are currently being employed in copious fields of applications due to their significant mechanical properties. These composite materials sometimes depart from their designed specifications as some defects, such as manufacturing defects, cause them to deviate from the expected enhancement in mechanical properties. These manufacturing defects involve misalignment, waviness, and sometimes breakage of fibers, fiber/matrix debonding, delamination, and formation of voids in the matrix of a composite material. An increase of 1% voids content in composites and leads to a decrease in tensile strength (10–20%), flexural strength (10%), and interlaminar shear strength (5–10%), respectively. It can be eradicated by manipulating the processing parameters of manufacturing processes [29].

Therefore, there is a need to understand and study different types of composite manufacturing techniques to implement optimized techniques that will avoid defects and give apposite self-sustaining, durable composite material that is efficient for the desired field of application. There are many conventional manufacturing techniques for fabrication of a composite material that have been in practice for the past few decades and some of the recently developed automated composite manufacturing techniques use robot assistance for processing, which leads to complete automation and an immense rise in productivity [30].

2. Classification

Composite materials are classified according to their content, i.e., base material and filler material. The base material, which binds or holds the filler material in structures, is termed as a matrix or a binder material, while filler material is present in the form of sheets, fragments, particles, fibers, or whiskers of natural or synthetic material. As represented in Figure 1, composites are classified into three main categories based on their structure [31].

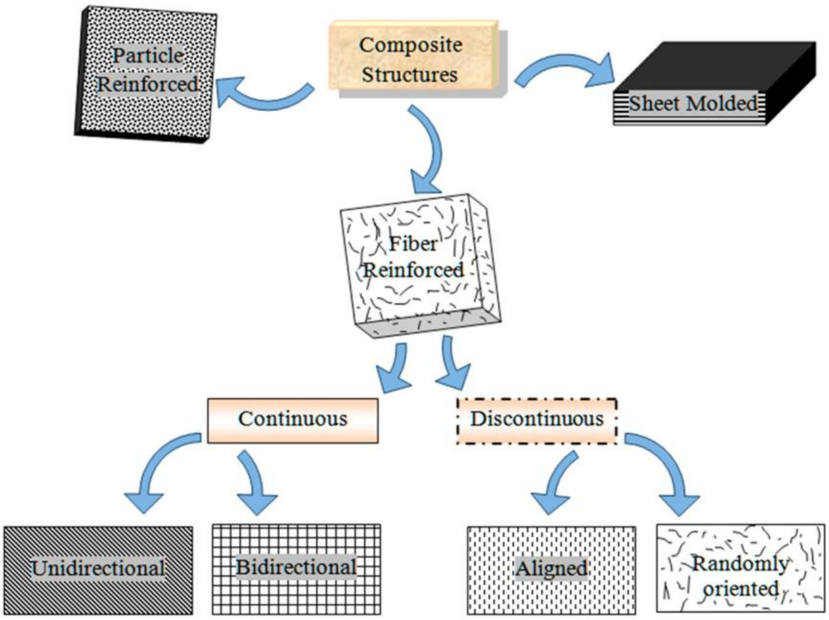

Figure 1. Classification of composites.

2.1. Fiber-Reinforced Composites

The length of the fibers used to make up a composite determines how the material is categorized. Continuous fiber reinforcement composites are those that have long fiber reinforcements while discontinuous fiber reinforcement composites are those that have short fiber reinforcements. When a single matrix structure incorporates reinforcement from many kinds of fibers, the resulting composite is called a hybrid fiber-reinforced composite [32]. Continuous fiber composites allow for the simple and efficient transfer of loads from the matrix to the fibers, regardless of whether the fibers are positioned in a bidirectional or unidirectional fashion inside the matrix structure. In order to prevent material failure in brittle matrices and to provide adequate load transmission, discontinuous fibers must be long enough to restrict the formation of fractures. Composite material characteristics and structural behavior are defined by the arrangement and orientation of fibers [33,34]. Chemically treating natural fibers improves their qualities, including impact toughness and fatigue strength. Traditional fiber-reinforced polymer (FRP) composite materials used scattered glass, carbon, basalt, or aramid fibers in their matrix structure [35,36]. Researchers are being driven to produce eco-friendly materials owing to strict environmental regulations, and natural fiber

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polymer composites (NFPCs) with significant qualities might find use in contemporary industry. There are numerous fibers available for composite materials and they are primarily categorized as natural or synthetic fibers. Further, recent studies have revealed unprecedented material properties when these two fibers are combined together, blending with a matrix material to form a hybrid composite. Some of the natural and synthetic fibers are shown in Figure 2.

Figure 2. Classification of fibers, reproduced from [37–53] under open access license.

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2.1.1. Synthetic Fibers

Synthetic fibers are man-made fibers that are created by chemical synthesis; these fibers may be further categorized as either organic or inorganic depending on their composition [54]. Fibers are a load-bearing component of composites due to their much greater strength and stiffness compared to the matrix material [55-59]. Because of their high strength-to-weight ratio, thermal stability, impact resistance, chemical resistance, friction, and wear resistance, glass fibers (GFs) are the most used synthetic fibers. But using traditional machining equipment to cut glass fiber-reinforced polymers (GFRPs) is a pain, takes forever, and wears out tools quickly [60]. Another drawback of GFs is the need to dispose of them after they have served their useful life [61].

However, carbon fibers (CFs) are used instead of GFs in applications that demand additional rigidity. Despite the benefits that other synthetic fiber types such as basalt, aramid, polyacrylonitrile (PAN-F), polyethylene terephthalate (PET-F), or polypropylene (PP-F) offer, they are not commonly used in thermoplastic short-fiber-reinforced polymers (SFRP). However, they have found use in certain applications where their desired properties are relevant [62]. Composites made of carbon fiber-reinforced polymer (CFRP) have found use in a wide variety of fields, including aerospace, automotive, and sports [63–65]. As the amount of carbon fibers in the material rose from 10% to 30%, the Young's modulus of solids rose by 78% and that of foams by 113%. Using carbon fiber/polypropylene (CF/PP) to create composite foams made by microcellular injection molding improved the cellular structure, which in turn improved the foams' Young's modulus by 35% [66].

Graphene fibers are a novel class of carbonaceous high-performance fibers that outperform carbon fibers in electrical conductivity and tensile strength. Lightweight conductive cables and wires, micromotors, solar cell textiles, actuators, knittable supercapacitors, and more are just a few of the many possible uses for graphene fibers, thanks to their improved characteristics [67,68]. Hardness, shear modulus, and Young's modulus were all shown to be 35% higher, 27.6% higher, and 150% higher, respectively, in the molecular dynamics simulation of polymer composites reinforcing graphene. There was also a 35% decrease in the coefficient of friction and a 48% decrease in the abrasion rate [69].

When compared to fiberglass, the physical and mechanical qualities of basalt fiber (BF) are superior. Also, compared to carbon fibers, BF is much more affordable. Research on basalt fiber-reinforced polymer (BFRP) composites has shown that when temperatures fall, fatigue life and static strength at a specific maximum stress both improve [70]. Although there is little study on hybridizing Kevlar fibers (KFs) with natural fibers, enhancing the thermal characteristics of Kevlar fiber-reinforced composites (KFRCs) with glass or carbon fibers is possible. Compared to glass and carbon fiber, KFRCs have poor compression strength because of their anisotropic structure, but they have strong impact strength and tensile qualities [71].

2.1.2. Natural Fibers

One naturally occurring material that is both abundant and simple to produce is natural fibers (NFs). Biodegradability, cheap cost per unit volume, high strength, and particular stiffness are some of the excellent material features that are shown by these tests. Reinforced NF composites seem to provide a number of advantages to synthetic fibers, including being lighter, cheaper, less hazardous, less polluting, and recyclable. Because of its superiority over synthetic fiber-reinforced composites in terms of both cost and environmental impact, NF composites have largely replaced them in recent years [33]. Natural fibers contain comparable structures but varied compositions, depending on the kind. Thermoset matrices that include both long and short natural fibers have shown promising high-performance uses [72,73]. Composites made of sisal fiber (SF) have excellent tribological qualities, making them a popular choice for furniture upholstery and car interiors. After polyester reinforcing SFs

reinforced with polyethylene (PE) composites, 6 mm long sisal fibers demonstrated a tensile strength of 12.5 MPa, and this strength increased with fiber volume [74-76]. In comparison to GF-reinforced composites with propylene matrices, hemp composites demonstrated a 52% improvement in specific flexural strength [77]. Reinforced with 15% weight of alkaline-treated hemp fibers, a composite material with 5% weight of maleic anhydride-grafted polypropylene (MAPP) and a polypropylene (PP) matrix showed an improvement of 68% in tensile strength and 37% in flexural strength, respectively [78]. The tensile strength of thermoplastic composites made of polylactic acid (PLA) and reinforced with kenaf fibers is 223 MPa, while the flexural strength is 254 MPa [79]. Additionally, kenaf fiber laminates' flexural and tensile characteristics are enhanced when absorbed water is removed from the fibers prior to lamination [80,81]. Composite materials containing 11.1% alkali-treated virgin kenaf fibers in unsaturated polyester matrix demonstrated flexural strengths of 69.5 MPa and 7.11 GPa, respectively, compared to 42.24 MPa and 3.61 GPa for unreinforced polyester samples [82]. Flax fiber-reinforced polypropylene composites (FF/PPs) have had their vibration and sound characteristics studied using a sound transmission loss (STL) test. Due to its strong sound absorption capabilities, the material exhibited an increase in stiffness, damping ratio, and mass per unit area as a consequence of an increase in transmission loss [83,84]. Laminates made of short flax fiber (FF) improved a material's tensile strength. In addition, according to reference 85, the shear modulus rose by 46% and the material strength by 15% when the fiber orientation was 45 degrees. Research on the free vibration properties of ramie fiber-reinforced polypropylene composites (RF/PPs) revealed that an increase in the damping ratio during flexural vibration occurs as a result of slippage between the fiber and the matrix caused by a greater fiber content in a polymer matrix. This suggests that the damping characteristics of RF/PP composites are improved as the fiber content increases [86,87]. The natural covering that develops around each grain of rice is called the rice husk (RH). Although it is considered agricultural waste, RH is actually used as reinforcement in composite materials to study how the qualities of these materials might be improved [88,89]. Optimal sound absorption capability was shown by polyurethane (PU) foam with 5% RH [90], which improved the material's acoustic properties. The best results were obtained from an impact test using a composite material that included 5% chicken feathers as reinforcement fibers and epoxy resin as the matrix material. There was a significant improvement in the material's tensile, flexural, and impact strengths when a hybrid composite made of chicken feathers, 1% carbon residuum (CR), and epoxy resin was utilized [91]. Based on research [92,93], it has been observed that the tensile strength and bundle strength of raw jute reeds decrease as the length of the reed increases. Composites made from the root portion of the reeds have a tensile strength that is 44% higher and a flexural strength that is 35% higher than composites made from the tip portion. Compared to composites reinforced with synthetic fibers, those made of randomly oriented coir fibers and polypropylene have superior damping capabilities. A greater resin concentration results in better damping qualities, which in turn allows for more energy absorption with lower fiber loading. The damping ratio reached its peak at 0.4736 with 10% fiber content in coir-PP composite. Adding 30% fiber content enhanced the material's natural frequency to 20.92 Hz [94,95]. An exceptional connection between the fibers and the matrix was seen in palm fibers (PFs). Another finding is that when palm fibers are added to low-density polyethylene (LDPE), the Young's modulus is greater than when homo-polymers are used [96]. At a fiber content of 3%, friction composites reinforced with abaca fiber (AF) exhibit an exceptional wear resistance property, with a wear rate of 2.864 × 10−7 cm3/Nm. Density was also shown to decrease when the abaca fiber percentage increased [97].

Mechanical properties such as tensile, compressive, flexural, impact, and water absorption characteristics are improved when luffa fibers (LFs) are used as a reinforcing component of composite material [98]. When 9.6 wt % LFs were added to an epoxy matrix, the density of the material decreased by 3.12%, leading to an even larger decrease in weight [99]. By using cotton fiber epoxy composite, the energy absorption and load-carrying characteristics of a tube material have been enhanced [100]. The processes and uses of producing various fibers and the components that make up their matrix are shown in Table 1.

Table 1. Matrix material used for some fibers with their applications and manufacturing techniques.

References	Materials Used		Application	Manufacturing Techniques
	Fiber Reinforcement	Matrix /Binder Material		
[64,65]	Carbon	PP, metals, ceramics, epoxy resin, Polyether ether ketone (PEEK)	Lightweight automotive products, fuel cells, satellite components, armor, sports.	Injection molding, filament winding, resin transfer molding (RTM)
[68]	Graphene	Polystyrene (PS), epoxy, Polyaniline (PANI)	Wind turbines, Gas tanks, aircraft/automotive parts.	CVD, pultrusion, hand/spray up method
[76]	Sisal	PP, PS, epoxy resin	Automobile body parts, roofing sheets	Hand lay-up, compression molding
[77]	Hemp	PE, PP, PU	Furniture, automotive.	RTM, compression molding
[80]	Kenaf	PLA, PP, epoxy resin	Tooling, bearings, automotive parts.	Compression molding, pultrusion
[83,84]	Flax	PP, polyester, epoxy	Structural, textile.	Compression molding RTM, spray/hand lay-up, vacuum infusion
[86,87]	Ramie	PP, Polyolefin, PLA	Bulletproof vests, socket prosthesis, civil.	Extrusion with injection molding
[89]	Rice Husk	PU, PE	Window/door frames, automotive structure.	Compression/injection molding
[92,93]	Jute	Polyester, PP	Ropes, roofing, door panels.	Hand lay-up, compression/ injection molding
[94,95]	Coir	PP, epoxy resin, PE	Automobile structural components, building boards, roofing sheets, insulation boards.	Extrusion, injection molding

2.1.3. Hybrid Fibers

In comparison to thermoset composites, the strength performance of thermoplastic composites reinforced with natural fiber is often rather low. Hybridizing these natural fiber composites with trace quantities of synthetic fibers makes them more appealing for technical uses, as it allows for greater design freedom and opens the door to recycling possibilities. The flexural modulus was measured at 5.5 GPa and the flexural strength was 101 MPa in hemp/glass fiber hybrid polypropylene composites with a filler content of 25% hemp and 15% glass by weight. The material's water-absorbing capabilities and impact strength were also thought to have been improved [101]. An SEM analysis of an epoxy hybrid composite reinforced with oil palm and kenaf fibers showed that the material's tensile and flexural strengths had been significantly enhanced due to the strong interfacial bonding between the fibers and the epoxy matrix. In addition, the hybrid material's superior energy absorption under impact loading makes oil palm/kenaf fiber hybrid composite a formidable rival in the automobile industry [102]. With a maximum interlaminar shear strength (ILSS) of 4.9 MPa and a hardness of 77.66 HRC, a hybrid composite made of carbon and flax fibers reinforced in an epoxy resin matrix reduced the material's average weight by 17.98% [103]. An exciting new approach, fiber hybridization involves combining the best qualities of several kinds of fibers into a composite matrix, therefore reducing the negative effects of each type while maximizing the positive ones. When the two fibers work together, the composite material gains advantages that would have been impossible with just one of the components alone [104,105]. A composite material that combines epoxy resin as its matrix with reinforcements of 27% banana and 9% jute fibers

yielded a modulus of rupture of 29.467 MPa. Compressive strength measurements for a different composite using the same matrix material and reinforcing with 21.5% coconut sheath and 15.5% jute fibers were

The pressure is 33.87 MPa. The tensile strength of the composite material was found to rise as the number of banana fiber reinforcements increased [106].

Part 2.2: Composite with Reinforced Particles

The material strength and fracture resistance characteristics of particle-reinforced composite (PRC) are not up to par with those of FRC. On the other hand, inorganic particles, metal, or ceramic particles limit the material's deformation and make it rigid. Because of their affordable price and isotropic features, PRCs have also been receiving some interest as of late. In addition, the production methods for these composites are quite comparable to those for monolithic materials [107,108]. When a high level of wear resistance is required, PRCs are used in civil applications like concrete buildings and highways. The binder in concrete is cement, while the hardness and stiffness are provided by the filler material, which is aggregate of coarse rock or gravel [109].

The 2.3. Composites Manufactured via Sheet Molding

Nonhomogeneous composite laminates are created by compressing homogeneous material layers together to create sheet-molded composites (SMCs). Adding more layers to a laminate makes it more resistant to buckling, which is especially true for FRP composites built of fiber sheets [110]. The use of SMC has been shown in large structural components with a high strength-to-weight ratio, such as portions of automobile bodies [111–113]. The chemical makeup of a material determines its tensile strength, which is a property of natural fibers. In general, the tensile strength of fibers goes up as their cellulose content goes up and down as their lignin content goes up. Table 2 shows some of the characteristics of commonly used fibers, and Table 3 shows the many characteristics provided by matrix material.

Composite ingredients and production methods aren't the only things that affect FRP composite performance.

The space around a fiber in the matrix phase of a fibreglass reinforced plastic (FRP) composite is called the interphase. The transfer from matrix to fiber occurs under loading circumstances during the interphase stress. Understanding the behavior of the interphase is crucial for evaluating the performance of composites, in addition to the characteristics of the individual components [33].

Table 2. Some significant properties of frequently used fiber materials [114–117].

Fiber	Density (g/cm^3)	Elongation (%)	Tensile Strength (MPa)	Young's Modulus (GPa)
Aramid	1.4	3.3–3.7	3000–3150	63–67
E-glass	2.5	2.5–3	2000–3500	70
S-glass	2.5	2.8	4570	86
Cotton	1.5–1.6	3–10	287–597	5.5–12.6
Hemp	1.48	1.6	550–900	70
Jute	1.3–1.46	1.5–1.8	393–800	10–30
Flax	1.4–1.5	1.2–3.2	345–1500	27.6–80
Ramie	1.5	2–3.8	220–938	44–128
Sisal	1.33–1.5	2–14	400–700	9–38
Coir	1.2	15–30	175–220	4–6
Kenaf	0.6–1.5	1.6–4.3	223–1191	11–60
Bamboo	1.2–1.5	1.9–3.2	500–575	27–40
Oil palm	0.7–1.6	4–8	50–400	0.6–9
Betel nut	0.2–0.4	22–24	120–166	1.3–2.6
Sugarcane bagasse	1.1–1.6	6.3–7.9	170–350	5.1–6.2

Pretreatments: Physical or chemical treatments like preheating, alkalization, acetylation, and use of silane coupling agent on fibers to modify the fiber surface and its internal structure results in the improvement of adhesion at the interface and amalgamation of the matrix resin into the fibers [118].

Size effect: For FRP-confined cylindrical concrete columns, size effect depends on the mode of failure; there is no occurrence of size effect if failure is plasticity dominated. When failure is fracture-dominated, it occurs due to shear banding. While in large columns, cylinders of small size fail due to FRP rupture caused by plastic dilation in the concrete [119].

Confinement methods: FRP-confined high strength concrete (HSC), and ultra-high-strength concrete (UHSC) show highly ductile compressive behavior when sufficiently confined. On the other hand, if HSC or UHSC are inadequately confined, there is degradation of the axial compressive performance of the FRP tube-encased or FRP-wrapped specimen. FRP thickness and confinement method does not make much difference in the strain reduction factor ($k\epsilon$), while for the concrete structures, $k\epsilon$ decreases with an increase in concrete compressive strength [120].

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Cross-section: Under concentric compression, the behavior of concrete-filled fiber-reinforced polymer tubes (CFFT) depends upon amount and type of tube material used, concrete strength, cross-sectional shape, specimen size, and manufacture method. When cross-sectional shape is taken into consideration, newly developed rectangular and square CFFT shows highly ductile behavior as a significant improvement with internal FRP reinforcement, when compared to conventional CFFTs [121]. Further studies have shown that specimen size does not influence the compressive behavior of CFFTs. Although a significant correlation has been observed between fiber elastic modulus and the strain reduction factor, fibers with a higher modulus of elasticity result in a decrease of the strain factor that further resembles concrete brittleness while manufacturing CFFTs [122].

Fiber volume: Maleic anhydride-grafted polypropylene (MA-g-PP) was used as a compatibilizer to improve adhesion between bamboo fiber and polypropylene matrix composite material. Composite with 5% MA-g-PP concentration and 50% fiber volume has increased impact strength by 37%, flexural strength by 81%, flexural modulus by 150%, tensile strength by 105%, and tensile modulus by 191%. When the fiber volume of chemically treated composite with MA-g-PP compatibilizer increased from 30% to 50%, it showed an increase in the heat deflection temperature (HDT) by 23 ◦C to 38 ◦C compared to virgin PP. Therefore, fiber volume of 50% fraction, 1–6 mm fiber length with 90–125 μm fiber diameters, coupled with MA-g-PP compatibilizer is the recommended optimized composition for bamboo fiber-reinforced polypropylene composites, which results in a maximum enhancement in the mechanical properties and a higher thermal stability is also achieved [123].

Table 3. Variety of available matrix materials.

References	Matrix Material	Properties	Applications
[2]	Polyethersulfone	Flame resistant	Automotive
[3]	Polyphenylene sulfide	Resistance to chemicals and high temperature	Electrical
[3,9]	Polysulfone	Low moisture absorption, high strength, low creep	Marine, food packaging
[6]	Polyethylene (PE)	Resistance to corrosion	Piping
[6,36,54,66,94,96,101]	Polypropylene (PP)	Resistance to chemicals	Packaging, automotive, construction
[6,13,79]	Polylactic acid (PLA)	Biodegradable, non-toxic	Food handling, bio-medical
[10,90]	Polyurethane (PU)	Wear resistance, low cost, sound and water-proof	Structural, acoustic
[16]	Poly(butylene adipate-co-terephthalate)-PBAT	Biodegradable, high stiffness	Coating, packaging
[19]	Cement	Durable	Structural
[28]	Poly(vinyl alcohol	High tensile strength	Bio-medical
[33]	Natural rubber	Low density, low cost, biodegradable	Structural, automobile
[54,91,98,100,102]	Epoxy resin	High strength	Automotive, aerospace, marine
[82,92]	Polyester	Durable, resistance to water, chemicals	Structural

Fiber orientation: When CO_2 laser engraving was employed for material removal of GFRP, it was found that surface roughness and machined depth of the laser-engraved surface were hugely dependent upon the fiber direction [60]. T300 carbon fibers and 7901 epoxy resin as a matrix material were used to fabricate T300/7901 unidirectional (UD) fiber-reinforced composite to investigate mechanical properties in uniaxial tension/compression and torsional deformations. Micrographs of fiber matrix interface at different load levels were examined, which revealed that matrix plastic deformation has no significant effect on predicted ultimate load at failure. It also revealed a noticeable drop in the ultimate strength with the increase in fiber angle from 0° to 15°. Stress concentration factor (SCF) plays an important role while considering the failure prediction, without consideration of SCFs transverse strength will be overestimated [124]. Thermal buckling load for curvilinear fiber-reinforced composite laminates is more for antisymmetric laminates, while laminates with nonuniform temperature distribution exhibit high critical load carrying capacity [110].

3. Manufacturing Techniques

Manufacturing of FRP composite involves manufacturing of fiber preforms and then reinforcing these fibers with the matrix material by various techniques. Fiber preforms involve weaving, knitting, braiding, and stitching of fibers in long sheets or mat structure [125–127]. Preforms are used to achieve a high level of automation with the assistance of robotics, which offers control over the fiber angle and the fiber content on every zone of the part to be molded [128].

3.1. Conventional Manufacturing Processes

Prepregs are a combination of fibers and uncured resin, which are pre-impregnated with thermoplastic or a thermoset resin material that only needs the temperature to be activated. These prepregs are ready-to-use materials where the readily impregnated layers are cut and laid down into the open mold [128]. Dow Automotive Systems has developed VORAFUSE, a technique that combines epoxy resin with carbon fiber for prepreg applications to improve material handling and cycle time in the compression molding of composite structures. Working in collaboration with a variety of automotive companies, they have achieved significant weight reduction, which results in efficient manufacturing of CFRP composite structures [129].

Figure 3 shows the hand lay-up, which is the most common and widely used open mold composite manufacturing process. Initially, fiber preforms are placed in a mold where a thin layer of antiadhesive coat is applied for easy extraction. The resin material is poured or applied using a brush on a reinforcement material. The roller is used to force the resin into the fabrics to ensure an enhanced interaction between the successive layers of the reinforcement and the matrix materials [130–132].

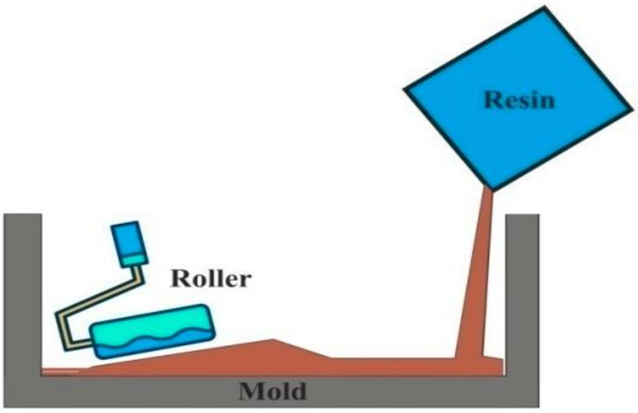

Figure 3. Hand layup process.

Spray-up technique is no different than hand lay-up. However, it uses a handgun that sprays resin and chopped fibers on a mold. Simultaneously, a roller is used to fuse these fibers into the matrix material. The process is illustrated in Figure 4. It is an open mold type of technique, where chopped fibers provide good conformability and quiet faster than hand lay-up [133,134].

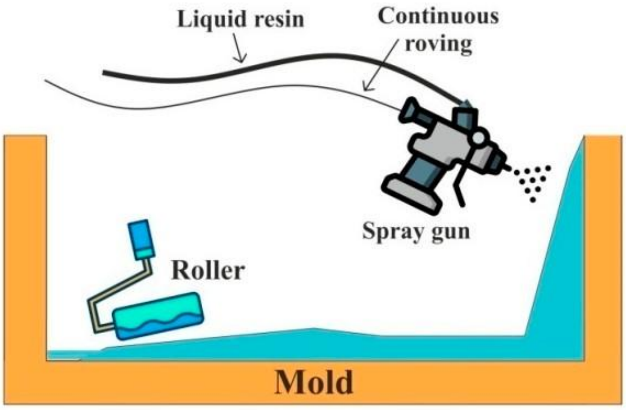

Figure 4. Spray-up process.

Vacuum bag molding uses a flexible film made of a material such as nylon polyethylene or polyvinyl alcohol (PVA) to enclose and seal the part from the outside air. Many times, the vacuum bag molding technique is performed with the assistance of the hand lay-up technique. Laminate is first made by using the hand lay-up technique, and then after it is placed between the vacuum bag and the mold to ensure fair infusion of fibers into the matrix material [135,136]. The air between the mold and the vacuum bag is then drawn out by a vacuum pump while atmospheric pressure compresses the part. The process can be well understood by Figure 5. Hierarchical composites were prepared with multiscale reinforcements of carbon fibers using a vacuum bagging process, which eliminated chances of detectable porosity and improper impregnation of dual reinforcements, with increases in flexural and interlaminar shear properties by 15% and 18%, respectively [137].

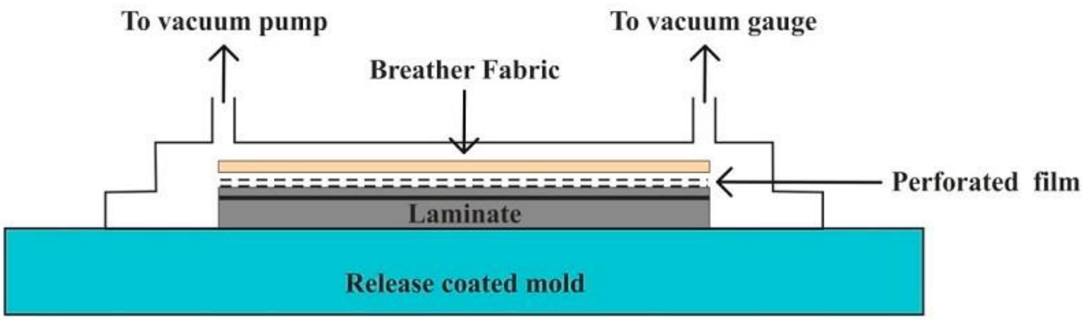

Figure 5. Vacuum bag molding process.

The preform fiber reinforcement mat or woven roving arranged at the bottom half of the mold and preheated resin is pumped under pressure through an injector [132]. The mechanism of the resin transfer molding (RTM) process can be understood with Figure 6. A variety of combinations of fiber material with its orientation, including 3D reinforcements, can be achieved by RTM [138,139]. It produces high-quality, high-strength composite structural parts with surface quality matching to the surface of the mold [140].

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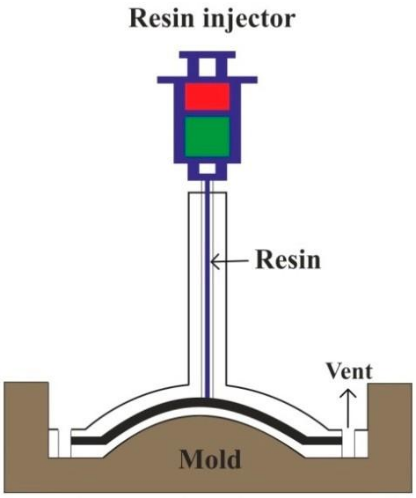

Figure 6. Resin transfer molding process.

4. Conclusions

Since its creation a century ago, composite materials have shown a plethora of improvements in many material characteristics. A lot of time and energy has gone into finding ways to improve the performance of materials so that they work better in certain uses. During the last few for many years, composites with reinforcements of fibers or particles in their matrix structure have shown remarkable properties, making them a preferred option for high-end uses.

The potential of diverse composite materials in different domains has been researched by studying their classifications and the qualities of its component parts. Among the many kinds of composites, fiber-reinforced material stands head and shoulders above the competition in the vast majority of high-profile applications.

When it comes to making fiber-reinforced composites, there is a wide variety of options, including both natural and synthetic fibers. While synthetic fibers are more rigid, natural fibers are more eco-friendly since they are both inexpensive and biodegradable. Recent studies have shown that hybrid fiber-reinforced composite materials work very well, as they combine the best features of both kinds of fibers. Nevertheless, both types of fibers are effective in some important applications.

Composites may be made using a wide variety of fabrication processes, and each of these methods works well with certain materials. Because various materials have varied physical properties—melting point, stiffness, tensile strength, etc.—the efficiency of a production procedure is reliant on the mix of matrix or fiber material type and volume. The choice of material so defines production procedures.

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