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Advanced Fiber-Reinforced Polymer Composites: Processing, Nano-Modified Adhesive Technologies, Interfacial Engineering, Durability, and Structural Applications—A Comprehensive Review

J. Faney[1],*, M. Hemapriya[2]

Abstract

Fiber reinforced polymer (FRP) composites are considered to be one of the most universal categories of advanced engineering materials owing to their unique properties such as outstanding strength-to-weight ratio, corrosion resistance, fatigue durability, and wide opportunities for design. Innovations in the fields of fiber reinforcement, polymer matrix system, composite manufacturing technologies, and nano-modified adhesives technology have greatly extended the range of applications of this type of materials in aerospace, automotive, marine, energy, biomedical, and civil engineering sectors. The current literature review provides an extensive analysis of recent advancements in FRP composites with special focus on manufacturing processes, nano-engineered adhesives, interfacial engineering, durability characteristics, and structural applications. In addition, this work includes critical analysis of the properties of various fiber reinforcement (carbon, glass, basalt, aramid, and novel natural fibers) and polymer matrix (thermosetting and thermoplastic) and their impact on the performance of composite. Recent advancements in manufacturing technologies (pultrusion, filament winding, resin transfer molding, additive manufacturing, automated fiber placement), in terms of microstructural properties and mechanical characteristics are analyzed. Special attention is given to nano-engineered adhesives including graphene, carbon nanotubes, nano-silica, and nanoclays. Moreover, the degradation pathways related to moisture, temperature, ultraviolet light, chemicals, and cyclic loading are studied in detail, along with the state-of-the-art characterization methods for interface evaluation. In addition, this review highlights the use of artificial intelligence and machine learning for the optimization of composite structures, defect detection, and assessment of their durability. Lastly, this paper identifies the gaps in the current research along with future challenges and directions related to biopolymers, recyclable composites, multifunctional materials, and smart health monitoring of composites.

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Keywords: Fiber-reinforced polymer composites; polymer matrices; nano-engineered adhesives; interfacial bonding; composite manufacturing; sustainable composites; structural applications

INTRODUCTION

Fiber reinforced polymers (FRPs) have been developed into one of the most prominent types of advanced engineering materials due to their high strength-to-weight ratio, great resistance to corrosion and fatigue, and excellent design versatility [1]. The materials in question consist of high performance fibers incorporated into polymer matrixes, leading to the creation of lightweight materials with superior mechanical and environmental properties. In turn, FRPs have become highly versatile in terms of usage and are employed in aerospace, automotive, marine, renewable energy, biomedical engineering, and civil engineering fields.

Modern advances in the field of polymer chemistry, composite processing technologies, and material engineering have made possible considerable advancements in the performance of FRP composites. Carbon fiber composites (CFRPs), glass fiber composites (GFRPs), basalt fiber composites (BFRPs), and aramid fiber composites (AFRPs) are highly valued due to their superior mechanical and durability characteristics. Furthermore, improvements in thermosetting and thermoplastic polymer matrixes, along with modern pultrusion, filament winding, resin transfer molding, and additive manufacturing technologies have allowed for the creation of high performance composite materials [2]. The latest advancement in nano-modified adhesion technology that involves the use of graphene, carbon nanotubes, nanosilica, and nanoclay indicates great promise in terms of interfacial engineering and environmental stability.

However, despite great progress in this area, some challenges persist in relation to durability in humid, thermal, ultraviolet light, chemical, and cyclic environments. Moreover, due to increased environmental concerns, there is an urgent need for research in the area of sustainable polymeric matrix systems and environmentally-friendly composite materials. While many review papers have been published covering specific areas related to FRP composite systems, relatively few studies are devoted to all mentioned issues [3].

Thus, this review discusses the recent advancements in the field of advanced fiber-reinforced polymer composites, focusing on their processing, nanomodified adhesive systems, interfacial engineering, durability, and structural applications. In addition, the current research limitations and future prospects associated with sustainable composite materials, characterization approaches, and intelligent composite design are presented to aid the advancement of next-generation polymer composite systems. Figure 1 shows the holistic concept of advanced fiber-reinforced polymer composites depicting the connections between reinforcing fibers, polymer matrix system, composite processing approaches, nanomodified adhesive systems, interfacial engineering, durability, and structural applications.

LITERATURE REVIEW

Recent studies have mainly concentrated on investigating the interaction between composite components, processing techniques, and interface interactions to enhance the functionality of FRP composites. An interphase-oriented review of polymer composites filled with nanofillers, synthetic fibers, and inorganic fillers was provided by Sachin Kumar Sharma et al. (2026). They concluded that the composite properties depend more on the interface adhesion, filler distribution, and microstructural changes due to processing rather than filler concentration only. It was further illustrated that there is a significant improvement in mechanical strength, thermal stability, and electrical performance of polymers through interphase manipulation. However, some limitations were reported in terms of filler agglomeration, dispersion of nanofillers, recyclability, and lack of processing technique for scaling up [4–5].

The recent developments in nanotechnology have also helped increase the rate of multifunctional composite polymers development. According to A. B. Rashid et al., the use of nanotechnology-based FRP composites was thoroughly analyzed, and it was established that addition of graphene, carbon nanotubes, nanosilica, and other nanofillers significantly increases the performance characteristics of these composites, including mechanical properties, thermal stability, electrical conductivity, and environmental durability. However, the authors note that there is still an issue of poor distribution of nanofillers, complicated process of production, high cost of manufacture, and absence of scalable manufacturing techniques [6].

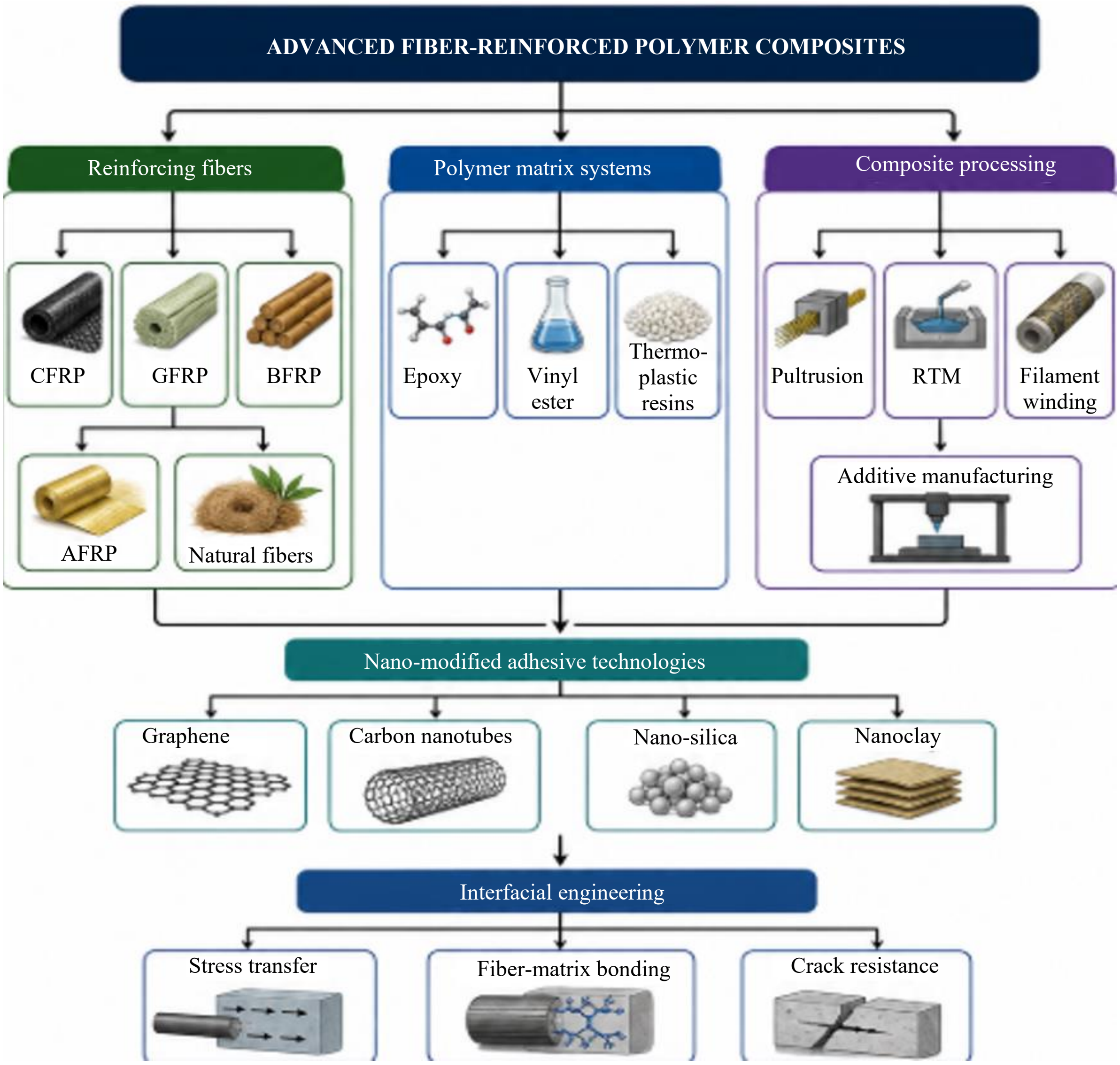

Figure 1. Integrated framework of advanced fiber-reinforced polymer composites.

Interface adhesion continues to be one of the main influencing elements in the long-term behavior of composite materials based on polymers. In their review, J. H. Kim et al. (2023) described the analysis of fiber/matrix wettability and interfacial adhesion assessment by various methodologies. It was shown that good wettability contributes to better stress transfer and mechanical properties through efficient bonding of reinforcing fibers with polymer matrices. The researchers analyzed several techniques used for interfacial adhesion estimation and showed that none of them can provide an adequate description of interphase behavior under service conditions. They advised combining several characterization techniques with microstructure analysis in order to understand failure modes at interfaces [7].

Although remarkable advancements have been made in the field of advanced polymer composites, previous research studies tend to address the specific areas like nanofiller reinforcement, surface treatment of fibers, adhesives, and processing techniques. An integrated study on composite processing, nano-modified adhesive technologies, interfacial engineering, durability, and structural applications is lacking. In addition to this, there are relatively fewer research studies that link the processing variables with interphase formation, environmental aging and sustainable composite development. Consequently, the present review paper attempts to fill these gaps through an integrated and critical discussion on advanced fiber reinforced polymer composites.

FIBER-REINFORCED POLYMER COMPOSITE MATERIALS

Classification and Characteristics of Fiber-Reinforced Polymer Composites

Fiber-reinforced polymer composites are high-performance materials that consist of reinforcing fibers reinforced in the polymer matrix. Reinforcing fibers add mechanical strength and stiffness to the material, while the polymer matrix holds fibers together and helps to transfer the load. The synergy of these materials results in light but mechanically strong and corrosion resistant structures with a very good fatigue resistance and long-lasting performance. Due to their properties, FRP composites are widely used in aerospace, automotive, maritime, renewable energy, biomedical and civil engineering applications [14].

Fiber-reinforced polymers composites can be differentiated based on the type of reinforcing fiber used in the material and include carbon fiber-reinforced polymer (CFRP) composites, glass fiber-reinforced polymer (GFRP) composites, basalt fiber-reinforced polymer (BFRP) composites, aramid fiber-reinforced polymer (AFRP) composites and natural fiber-reinforced polymer composites. These reinforcements have their own unique characteristics regarding strength, stiffness, durability, thermal stability, and cost, therefore are used in different fields of engineering. Also, there are thermosetting polymer matrices, which include epoxy, vinyl ester and polyester resins, as well as thermoplastic polymers, namely polypropylene, polyamide and polyether ether ketone (PEEK) [8].

In recent times, the development of composites has been more towards enhancing fiber-matrix interactions through sophisticated manufacturing technologies, surface treatments, and nanocomposites. Such innovations have not only increased the bonding efficiency and durability of the composites but have also expanded their applicability in engineering components of higher performance. Figure 2 depicts the classification of FRP composites depending on reinforcing fibers and polymers matrices.

Reinforcing Fibers and Their Performance

The behavior of fiber reinforced polymer (FRP) depends on the nature of the reinforcement fibers that are incorporated into the FRP to impart strength and stiffness to the polymer matrix. Considering various types of reinforcement fibers used, CFRP has maximum strength and stiffness among others. Thus, it is widely used in aerospace and high load structural applications. However, due to high cost of production, CFRP cannot be used for large scale commercial purposes. On the other hand, GFRP is less expensive material that can resist corrosion but has low stiffness and thus cannot perform efficiently under high loads. The recent focus of research has been on the development of BFRP due to their combination of properties

Table 1. Comparative properties of commonly used reinforcing fibers in polymer composites.

Fiber Type	Density (g/cm³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Major Advantages	Major Limitations	Typical Applications
CFRP	1.75–1.95	3500–7000	230–600	High strength, excellent fatigue resistance	High cost	Aerospace, bridges, wind turbines
GFRP	2.45–2.60	2000–3500	70–85	Economical, corrosion resistant	Lower stiffness	Marine, automotive, construction
BFRP	2.60–2.80	2800–4800	85–95	Thermal stability, eco-friendly	Limited long-term field data	Civil structures, transportation
AFRP	1.40–1.45	2800–3600	70–180	High toughness, impact resistance	UV and moisture sensitivity	Defence, aerospace, protective structures
Natural Fibers	1.20–1.50	200–1000	10–80	Renewable, biodegradable	Moisture absorption, lower durability	Automotive interiors, packaging, green composites

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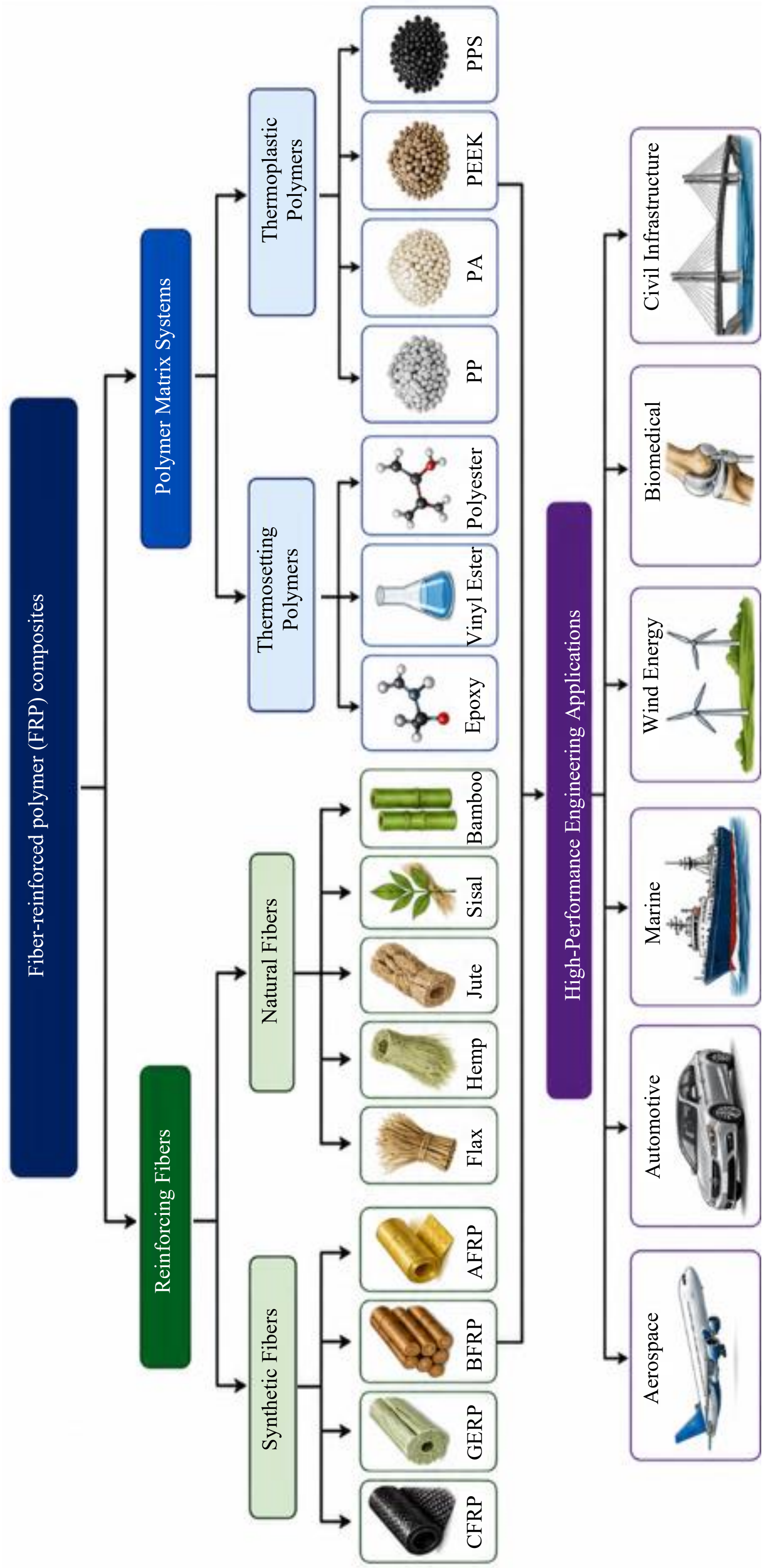

Figure 2. Classification of fiber-reinforced polymer composites.

Natural fibers like flax, hemp, jute, sisal, and bamboo have also gained popularity over the years as sustainable reinforcing materials due to their sustainable sources and low environmental effect. Nonetheless, their inferior mechanical properties and susceptibility to moisture still inhibit their use in structurally critical conditions.

The choice of reinforcement fiber must take into account mechanical strength, durability, environmental conditions, ease of production, and economy [9]. A table comparing the properties of some reinforcing fibers is shown in Table 1 below.

Current Trends and Research Challenges

Innovations in fiber-reinforced polymer composites have centered on achieving multifunctionality using innovative materials, sustainable reinforcement approaches, and intelligent manufacturing technologies. Multifunctionality has been achieved through hybrid composite materials that use carbon, glass, basalt, and natural fibers. The hybrid composite materials have resulted in better mechanical behavior without high costs of production.

Besides, nano-composites made up of graphene, carbon nanotubes, nanosilica, and nanoclay are increasingly used due to their ability to improve interfacial adhesion, fracture toughness, thermal stability, and electrical conductivity. Environmental issues have pushed forward innovations in the production of recyclable thermoplastic composites and biopolymer composites.

In spite of these developments, there are still quite a few issues that require resolution. Ensuring homogenous dispersion of the nanofillers, improving compatibility between the fibers and the matrix, decreasing manufacturing cost, making the composite recyclable, and developing standard ways of assessing the durability of the FRP are all among the current topics of scientific interest. Besides, the issue of performance under harsh environmental conditions, such as moisture, UV radiation, temperature cycles, and chemical exposure, needs further study. Meeting these challenges through the use of advanced materials science, innovative manufacturing technologies, and environmentally friendly manufacturing methods will make it possible to create next-generation polymer composites. They will form the basis of the following discussion about the polymer matrix systems.

POLYMER MATRIX SYSTEMS

The mechanical properties of fiber-reinforced polymer (FRP) composites depend significantly upon the performance of polymer matrices. These matrices hold fibers together, transfer stresses and strains, prevent corrosion and degradation of fibers, and preserve integrity of the FRP composite structure. The selection of a matrix material affects not only mechanical properties but also thermal stability, chemical resistance, processibility, and recyclability of the composite. Taking into account the nature of the matrix material and its processibility, polymer matrices are generally divided into thermosetting and thermoplastic polymers.

Thermosetting and Thermoplastic Polymer Matrices

Thermosetting polymer matrices, which include epoxy resin, vinyl ester resin, and unsaturated polyester resin, are extensively used in composite structures due to their good mechanical properties, thermal stability, and good bond strength with reinforcement fibers. Of these, epoxy resins are the most favored matrices owing to their exceptional bonding properties, low shrinkage, and chemical resistance.

On the other hand, thermoplastic polymer matrices like polypropylene (PP), polyamide (PA), polyether ether ketone (PEEK), and polyphenylene sulfide (PPS) have recently attracted a lot of attention due to their recyclable nature, fast processing, fracture toughness, and impact strength. Despite the higher processing temperatures involved, thermoplastic composites can be easily processed on a large scale. The key differences between the two types of matrices are presented in Table 2.

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Recent Developments and Future Trends in Polymer Matrix Systems

Modern studies have emphasized the development of high performance polymer matrices possessing good mechanical properties, strength, and sustainability. Nano-reinforced resin matrices using graphene, carbon nanotube, nanosilica, and nanoclay have exhibited better interfacial bonding, fracture resistance, and thermal stability. Furthermore, biopolymer matrices and recyclable thermoplastics are also being increasingly used for addressing the issue of minimizing the effect on the environment and adopting sustainable manufacturing processes. However, there still exist difficulties like complex processing, high cost, durability, and scalability for large-scale industrial use. Hence, future research should be oriented towards developing multifunctional polymer matrices which possess excellent mechanical performance, sustainability, and intelligence [10].

COMPOSITE PROCESSING TECHNIQUES

The processing method is highly significant to ensure the properties and behavior of fiber reinforced plastic (FRP) composite materials. The appropriate processing leads to the even dispersion of fibers, complete infiltration of the resin matrix, lower voids, and high fiber matrix bonding strength. The choice of an appropriate processing technique is dependent on the kind of reinforcement, polymer matrix, form of product, and application purpose.

Conventional Composite Manufacturing Techniques

Traditional techniques like hand lay-up, filament winding, pultrusion, compression molding, and RTM continue to be employed because of their ease of use and economic feasibility. Hand lay-up is ideal for big composite structures, whereas filament winding and pultrusion work best for creating pipes and pressure vessels. RTM provides greater dimensional accuracy and lower incidence of voids, making it an optimal choice for high-performance composite parts.

Advanced Processing Technologies and Future Trends

Recent advancements have seen the advent of more sophisticated manufacturing processes such as AFP, 3D printing, and robotic composite manufacturing that have increased production efficiency and product quality. They facilitate accurate fiber placement, reduced waste, and increased repeatability. Furthermore, digital manufacturing and artificial intelligence-aided process optimization techniques are used to detect defects and enhance the performance of composite materials. Future research will concentrate on sustainable manufacturing, recyclable composite manufacturing, and intelligent manufacturing systems for future generations of polymer composites [12]. Some of the major conventional and advanced manufacturing techniques of composites used to manufacture FRP composites include those listed in Figure 3. Table 3 provides a comparison of major composite manufacturing techniques based on their strengths and weaknesses and common engineering applications.

Table 2. Comparison of thermosetting and thermoplastic polymer matrices used in FRP composites.

Matrix Type	Examples	Major Advantages	Major Limitations	Typical Applications
Thermosetting	Epoxy, Vinyl Ester, Polyester	High strength, excellent adhesion, chemical resistance	Non-recyclable, brittle after curing	Aerospace, marine, civil structures
Thermoplastic	PP, PA, PEEK, PPS	Recyclable, high toughness, rapid processing	Higher processing temperature and cost	Automotive, biomedical, aerospace

Table 3. Comparison of commonly used composite processing techniques.

Processing Technique	Advantages	Limitations	Typical applications
Hand Lay-up	Simple, low cost	Labour-intensive	Marine, construction
Filament Winding	High fiber alignment	Limited to cylindrical components	Pipes, pressure vessels
Pultrusion	Continuous production	Constant cross-section only	Structural profiles
RTM	Good surface finish, low voids	Higher tooling cost	Automotive, aerospace
Additive Manufacturing	Complex geometries, less waste	Slow production rate	Biomedical, aerospace

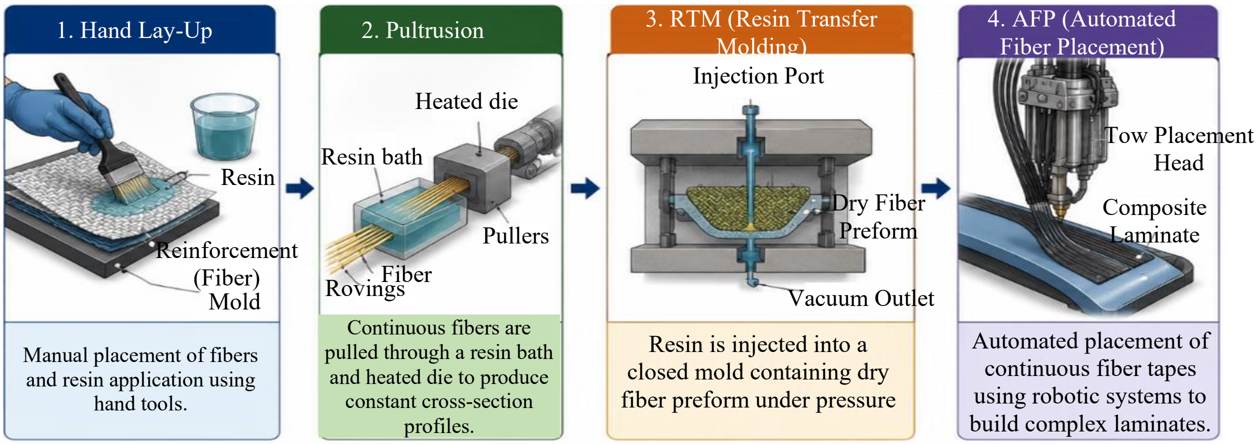

Figure 3. Composite processing techniques.

NANO-MODIFIED ADHESIVE TECHNOLOGIES

Nanotechnology-enhanced adhesive systems have proved to be an efficient way to increase the performance of FRP composites through the improvement of the fiber–matrix interfacial bonding and stress transfer efficiency. Epoxy resins represent popular adhesives due to good adhesion, chemical resistance, and mechanical properties; yet, the usage of various nanomaterials like graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), nanosilica, and nanoclay has greatly increased the fracture toughness, tensile strength, thermal stability, and fatigue resistance of materials. These nanofillers decrease microcrack formation and increase load transfer at the interface, increasing the durability of the composite system under moisture, heat, and chemicals. Recent developments also involved bio-adhesive systems to increase sustainability and prolong the service life of the polymer composites. Nevertheless, there is a number of problems, including nanomaterial distribution issues, high costs of production, and difficulty in implementation on an industrial scale, that should be addressed further. The development of optimized nanoengineered adhesive systems with superior mechanical properties, environmental durability, and sustainable manufacturing process should be the main goal of future studies [11].

INTERFACIAL ENGINEERING AND BONDING MECHANISMS

Interface engineering plays an important role in FRP composites, as the fiber-matrix interface plays an important role in the process of stress transfer, crack propagation, mechanical performance and durability [13]. Efficient adhesion at the fiber-matrix interface contributes to efficient stress transfer from the matrix to the fibers and enhances tensile strength, stiffness, impact properties and fatigue behavior. New developments in surface modification technologies, such as plasma treatment, chemical modification, silane treatment, and nano-coating, contribute to improved fiber-matrix adhesion and minimized interface defects. Moreover, adding nanomaterials like graphene, carbon nanotubes and nanosilica to the interface contributes to increased fracture resistance and environmental stability.

However, interfacial debonding, fiber pullout, delamination and environmental aging remain important problems for interface engineering in composites. In this respect, future research should be focused on developing multifunctional interface engineering concepts in order to improve bonding efficiency and durability of new-generation composite materials [15].

FUTURE PERSPECTIVES

Future research work on fiber-reinforced polymer composites can be anticipated to address the design and processing of multifunctional composites, offering mechanical superiority, durability, and sustainability. Future advances in terms of nanoscale engineered polymers, intelligent adhesives, and surface treatment methods are expected to facilitate better fiber-matrix interaction and increase the service life of the composite structure.

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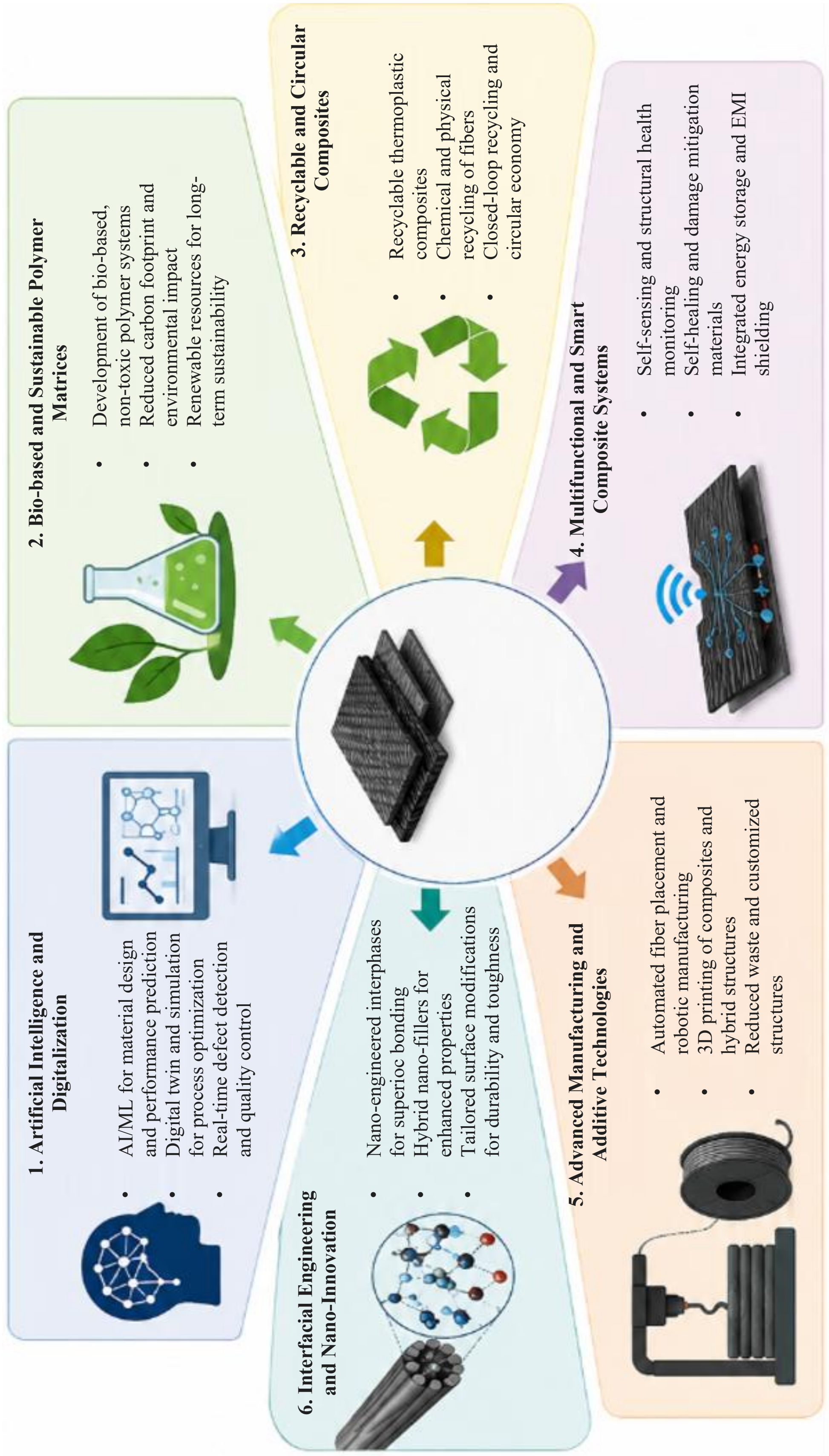

Figure 4. Future perspectives highlighting sustainable materials.

Table 4. Recent research progress and future research opportunities in advanced FRP composites.

Research area	Recent advances	Current challenges	Future research opportunities
Reinforcing fibers	Hybrid and high-strength fibers	High cost and recyclability	Sustainable hybrid reinforcement systems
Polymer matrices	Bio-based and thermoplastic matrices	Processing complexity	Recyclable and self-healing polymers
Composite processing	AFP, RTM, 3D printing	Manufacturing cost	AI-assisted smart manufacturing
Nano-modified adhesives	Graphene, CNT, nanosilica	Nanofiller agglomeration	Multifunctional nano-adhesives
Interfacial engineering	Surface modification and nano-coatings	Long-term durability	Intelligent interface engineering
Durability	Environmental aging studies	Lack of long-term field data	Predictive durability modelling
Sustainability	Circular composites	Recycling efficiency	Green manufacturing technologies

Additionally, increased use of biopolymer composites, recycling capability of thermoplastic composites, and eco-friendly manufacturing process is expected to lead to sustainable composite materials. Advanced manufacturing technologies such as artificial intelligence and machine learning technology are also expected to be used to improve composite design, defect detection, and process control and develop reliable composites. The recent progress in research, existing problems, and future research work in advanced fiber-reinforced polymer composites are presented in Figure 4. Recent progress in research work, existing problems, and future research work in advanced FRP composites are shown in Table 4.

CONCLUSIONS

Fiber reinforced polymers (FRPs) have become innovative engineering materials due to their high strength-to-weight ratio, resistance to corrosion, durability, and versatility. In this review, recent developments on reinforcing fiber types, polymer matrix compositions, composite manufacturing methods, nano-enabled adhesives and interfacial engineering, all of which affect the performance of advanced polymer composites, have been considered. It has been pointed out that the combination of high-performance reinforcing fibers with well-designed polymer matrices and nano-modified adhesives can provide improved properties, bonding, and durability.

Recent innovations in manufacturing technologies of composites, sustainable polymer systems, and nanotechnology have increased the use of FRPs in aerospace, automotive, marine, renewable energy, and civil infrastructure industries. However, some problems such as interfacial deterioration, environmental aging, recyclability, and large-scale affordable production still hinder wide utilization of FRPs. Solving the aforementioned issues will be possible through development of multifunctional materials, environmentally friendly polymer matrices, characterization methods, and intelligent manufacturing.

In summary, the ongoing evolution of polymer sciences, nanotechnologies, and composite technologies is anticipated to speed up the emergence of the new generation of FRP composites that will have improved mechanical properties, durability, and sustainability. The results discussed in this review provide a holistic view on the achievements and prospects of research in this area and thus can serve as an excellent source of information for researchers and engineers working with advanced polymer composites.

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