Journal Of Research Technology & Engineering
www.jrte.org

Sustainability Analysis of Fiber-Reinforced Polymer Composites

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Received:02 July 2023; Revised: 05 July 2023; Accepted: 07 July 2023; Available online: 10 July 2023

Abstract: Natural Fiber Reinforced Polymer Composites (NFRPCs) have emerged as a promising alternative to traditional synthetic polymer composites, offering improved sustainability in various applications. This paper provides an overview of the potential benefits of NFRPCs in improving the sustainability of applications, including reduced environmental impact, enhanced biodegradability, and increased use of renewable resources. The paper highlights the key factors that affect the properties and performance of NFRPCs, such as fiber type, fiber content, processing methods, and environmental conditions. The potential applications of NFRPCs in various sectors, such as construction, automotive, and packaging, are also discussed. This paper also concludes that NFRPCs have significant potential for improving sustainability in various applications, and further research and development in this area can help to accelerate the adoption of NFRPCs as a more sustainable alternative to traditional synthetic polymer composites.

Index Terms: Biodegradability, Natural Fiber Reinforced Polymer Composites, Sustainability, Design flexibility

1 . Introduction

Composite materials are materials composed of two or more distinct components that, when combined, produce a material with properties that are different from those of its individual components. The components may be of different chemical nature or may be of the same chemical nature but in different physical forms. The main components of a composite material are typically referred to as the matrix and the reinforcement [1]. The matrix is the material that binds the reinforcement together, while the reinforcement is the material that provides the desired properties of the composite [2].

Composite materials have become increasingly utilized in engineering applications due to their specific characteristics, including high strength-to-weight ratios, excellent durability, and resistance to fatigue, corrosion, and temperature resistance, which make them ideal for a wide range of industrial applications [3], [4]. When compared to conventional materials such as metal, plastics, the usage of composites is rapidly increasing worldwide. They are commonly used in the industries such as aerospace, automotive, marine, construction, and sports due to their specific attributes. Here are some of the key reasons why composite materials are more important for modern applications [5].

1. Lightweight and high strength: Composites are lightweight and have high strength-to-weight ratios, making them ideal for applications where weight is a critical factor for certain applications. As an example, composite materials are more applicable in aerospace and automotive industries to reduce weight and increase fuel efficiency [6], [7].
2. Durability and corrosion resistance: Composite materials are highly durable and have excellent

resistance to corrosion, making them ideal for use in harsh environments [8]. As an example, composite materials are commonly used in marine and offshore applications where resistance to saltwater corrosion is essential.

3. Design flexibility: Composite materials generally offer a high degree of design flexibility, allowing engineers to create complex shapes and structures that would be difficult or impossible to achieve with traditional materials. This flexibility enables designers to optimize performance, reduce weight, and increase functionality and performance.
4. Energy efficiency: Composite materials can help reduce energy consumption in a variety of applications. As an example, wind turbine blades made from composite materials are lighter and more efficient, leading to increased energy production and reduced costs.
5. Cost savings: While composite materials can be more expensive than traditional materials, they can often provide significant cost savings in the long run. For example, composite materials used in aircraft can reduce fuel consumption, leading to lower operating costs over the lifetime of the aircraft.

The manufacturing process for composite materials varies depending on the type of composite being produced. However, it typically involves combining the matrix and reinforcement materials through a process of molding, curing, and shaping. As composite materials offer unique properties that make them desirable for various applications, their use is expected to continue to grow in the future.

2. Types of Composites

There are various types of composite materials available, including fiber-reinforced composites, particulate composites, and laminates. But fiber-reinforced composites are the most common type and consist of matrix material, such as polymer resin, reinforced with fibers, such as carbon, glass, or Kevlar. Here are some of the most common types of composites. As the first one, fiber-reinforced composites are prominent type of composite which is made up of a polymer matrix reinforced with fibers, such as carbon, glass, or aramid. The fibers provide strength and stiffness, while the matrix material binds the fibers together and transfers the load. The fibers of these composites may either be natural or synthetic [9], [2]. According to the fiber length FRP composites can be classified. Composites reinforced with long fibers are called as continuous FRP composites while composites reinforced with short fibers are called discontinuous FRP composites [10]. Particulate composites generally consist of a matrix material reinforced with particles, such as metal or ceramic. The particles provide strength and improve wear resistance [11], [12]. Laminated composites are made up of multiple layers of materials, such as fibers, fabrics, or films that are bonded together with a matrix material. The layers can be oriented in different directions to provide specific properties, such as stiffness and strength [12]. Sandwich composites consist of two outer layers, or skins, that are bonded to a core material, such as foam or honeycomb. The skins provide strength and stiffness, while the core provides insulation and support. Ceramic matrix composites are made up of a ceramic matrix reinforced with ceramic fibers or particles. They are highly resistant to high temperatures and can be used in applications such as gas turbines and aerospace components [13]. Metal matrix composites consist of a metal matrix reinforced with fibers, particles, or whiskers and they are highly resistant to wear and can be used in applications such as brakes and engine parts [14]. The selection of the appropriate composite type depends on the specific requirements of the application, such as strength, stiffness, durability, and temperature resistance. Among these types, FRP composites have gained significant attention as they have some special attributes such as high strength, high stiffness, and low weight. This review mainly focuses on the importance of FRP composites for industrial applications.

3 . FIBER-REINFORCED POLYMER COMPOSITES

Fiber-reinforced polymer (FRP) composites are a type of composite material that consists of a polymer matrix reinforced with fibers. The fibers are typically made from carbon, glass, or aramid, and provide the strength and stiffness of the composite. As they are considered high-performance materials, these materials are widely used in a variety of industries, including aerospace, automotive, construction, and marine, due to their high strength-to-weight ratio, corrosion resistance, and durability [9]. Some common applications of FRP composites include:

1. Aerospace: FRP composites are used in the construction of aircraft and spacecraft due to their high strength and lightweight properties. They are used in components such as wings, fuselages, and engine parts [15], [5].
2. Automotive: FRP composites are used in the automotive industry to reduce weight and increase fuel efficiency. They are used in components such as body panels, bumpers, and interior trim [15], [5]. Many researchers have proven that the usage of natural composite materials for both structural and non-structural parts of vehicles has a lower environmental impact [16], [5]. Carbon fiber reinforced polymers are increasingly used for the external components of a vehicle.
3. Construction: FRP composites are used in construction applications due to their high strength and durability. More than 20% of manufactured FRP are used in components such as rebar, bridge decks, and building facades [17], [7]. By today, the use of FRP is spreading towards the manufacturing of transportation infrastructure owning its durability and higher mechanical properties in addition to construction of buildings. As an example, bridge construction uses FRP reinforcements. There are so many growing features can be seen in this sector as the demand is increasing for the sustainable and energy efficient building structures. As well as, FRP have been widely used for the repairing of deteriorated bridge and to reconstruct conventional concrete bridges [18].
4. Marine: FRP composites are widely used in the marine industry due to their resistance to corrosion and high strength. They are used in components such as boat hulls, masts, and rigging [19]. At present, FRP are widely used for the construction of ship hulls instead of the metals [15].

The manufacturing process for FRP composites typically involves impregnating the fiber reinforcement with the polymer matrix and then curing the composite under controlled conditions. The resulting material can be molded into a wide range of shapes and sizes, making it highly versatile and suitable for a wide range of applications. Fiber-reinforced polymer (FRP) composites are broadly classified into three types based on the type of fiber used:

1. Carbon fiber reinforced polymer (CFRP) composites: These composites are reinforced with carbon fibers, which offer high strength and stiffness. CFRP composites are commonly used in aerospace, automotive, and sporting goods applications [19].
2. Glass fiber reinforced polymer (GFRP) composites: These composites are reinforced with glass fibers, which are relatively inexpensive and offer good strength and stiffness. GFRP composites are commonly used in construction and marine applications [19].
3. Aramid fiber reinforced polymer (AFRP) composites: These composites are reinforced with aramid fibers, which offer high strength and resistance to impact and wear. AFRP composites are commonly used in military and protective equipment applications [19].

FRP composites can also be classified based on the type of matrix used, such as epoxy, polyester, vinyl ester, or thermoplastic [20]. The choice of matrix material depends on the specific requirements of the application, such as the level of strength, stiffness, durability, and temperature resistance needed. In addition to these types, hybrid composites can also be produced by combining different types of fibers and matrices. Many properties of natural fibers can be improved by the hybridization [21]. For example, a hybrid composite may be produced by combining carbon fibers with glass fibers to achieve a balance of strength and cost.

4 . NATURAL FIBERS AND NATURAL FIBER REINFORCED POLYMER COMPOSITES

Natural fibers are fibers that are derived from plants, animals, or other renewable sources. They are used in a variety of applications, including textiles, paper, composites, and construction materials. They are also used to produce bio composites, including their renewable nature, biodegradability, and low environmental impact [22]. Some examples of natural fibers include cotton, hemp, flax, jute, wool, silk, and bamboo. Cotton is one of the most widely used natural fibers in the world. It is soft, breathable, and absorbent, making it ideal for clothing, bedding, and other textiles. Hemp is a fast-growing plant that produces strong and durable fibers. It can be used to make a variety of products, including clothing, paper, and construction materials. Flax fibers are derived from the stems of the flax plant. They are strong, absorbent, and have a natural luster, making them ideal for textiles and other applications. Jute is a vegetable fiber that is commonly used to make burlap and other coarse fabrics. It is also used in the construction industry as a natural insulation material. Wool is a natural fiber that is derived from the fleece of sheep or other animals. It is warm, durable, and naturally flame-resistant, making it ideal for clothing and other applications. Silk is a natural protein fiber that is derived from the cocoons of silkworms. It is soft, lustrous, and strong, making it ideal for clothing and other textiles. Bamboo fibers are derived from the bamboo plant. They are soft, durable, and naturally antimicrobial, making them ideal for clothing and other textiles. Natural fiber-reinforced polymer (NFRP) composites are a type of composite material that consists of a polymer matrix reinforced with natural fibers, such as jute, flax, hemp, bamboo, and kenaf. These composites are gaining popularity due to their eco-friendliness, biodegradability, low cost, and excellent mechanical properties [22]. Some common applications of NFRP composites include:

1. Automotive: NFRP composites are used in the automotive industry to reduce weight and increase fuel efficiency. They are used in components such as dashboards, door panels, and interior trim [23].
2. Construction: NFRP composites are used in construction applications due to their high strength and durability. They are used in components such as roofing sheets, wall panels, and door frames [24].
3. Packaging: NFRP composites are used in packaging applications due to their lightweight and biodegradability. They are used in components such as packaging trays, bags, and boxes [25].

The manufacturing process for NFRP composites is similar to that of traditional FRP composites, involving impregnating the natural fiber reinforcement with the polymer matrix and then curing the composite under controlled conditions. The resulting material can be molded into a wide range of shapes and sizes, making it highly versatile and suitable for a wide range of applications.

5 . DISCUSSION

5.1 Sustainability of Natural Fiber reinforced polymer composites

Natural fiber-reinforced polymer composites have gained significant attention in recent years due to their eco-friendly nature, low cost, and lightweight. However, their sustainability depends on several factors, including the type of natural fiber used, the type of polymer matrix, the processing techniques, and end-of-life disposal. One of the main advantages of natural fiber-reinforced polymer composites is their biodegradability nature. Biodegradability refers to the ability of a material to be broken down and decomposed by natural biological processes, such as the action of microorganisms like bacteria and fungi, into simple and harmless substances like water, carbon dioxide, and biomass. In the case of NFRPCs, biodegradability refers to the ability of the composite to break down into its natural components, such as the natural fibers and polymer matrix, under natural conditions [26]. The biodegradability of NFRPCs is an important factor in their environmental impact, as it determines how long they persist in the environment and how they ultimately affect the ecosystem. NFRPCs that are more biodegradable can potentially offer a more sustainable alternative to traditional synthetic polymer composites, which can persist in the environment for hundreds of years without breaking down. The biodegradability of NFRPCs can depend on various factors, such as the type and composition of the natural fibers and polymer matrix, the processing methods used to create the composite, and the environmental conditions under which it is disposed of. The attention for manufacturing green composites has been rapidly increased due to this specific property. For that, natural fibers provide huge contribution as they consume lower energy in producing NFRPC than conventional composites [27].

The revenue generated from manufacturing natural fibers can vary depending on the type of fiber, the scale of production, and the market demand. However, the industry can also face challenges such as competition from synthetic materials, changing consumer preferences, and supply chain disruptions Some of the commonly used natural fibers in the manufacturing industry include cotton, wool, silk, flax, hemp, jute, sisal, bamboo, and coir. The revenue generated from manufacturing natural fibers can come from several sources, including:

1. Raw material sales: Natural fibers are typically sold in bulk to manufacturers who use them to produce various products. The revenue generated from raw material sales depends on the market demand, the quality of the fiber, and the supply chain costs [28].
2. Finished product sales: Natural fibers can be used to produce a wide range of finished products, such as textiles, paper, and building materials. The revenue generated from finished product sales depends on the market demand, the quality of the finished product, and the competition [29].
3. Export sales: Natural fibers are often exported to other countries where they are used in manufacturing. The revenue generated from export sales depends on the market demand, the quality of the fiber, and the competition in the global market.
4. Value-added services: Some natural fiber manufacturers may offer value-added services such as processing, spinning, and weaving, which can generate additional revenue.

.Natural fibers are derived from renewable sources, such as plants and animals, and can be easily decomposed by microorganisms in the soil. On the other hand, the polymer matrix used in the composites may not be biodegradable, which can limit the sustainability of the composites. To overcome this issue, researchers have been developing biodegradable polymer matrices, such as Polylactic acid (PLA), Polyhydroxyalkanoates (PHAs), and cellulose-based materials [30]. These biodegradable polymers can be used to replace traditional petroleum-based polymers, which can enhance the sustainability of natural fiber-reinforced polymer composites. The processing techniques applied to manufacture natural fiber-reinforced polymer composites can also affect their sustainability. The use of environmentally friendly processing techniques, such as water-based processing, can reduce the harmful environmental impact of the composites. End-of-life disposal is another important factor to consider in the sustainability of natural fiber-reinforced polymer composites. When the composites reach the end of their useful life, they can be recycled, composted, or incinerated. Recycling and composting are preferred as applicable options, as they can help reduce waste and conserve natural resources in an effective way. It is required to minimize material cost, and weight and to offer sustainable solutions over synthetic fibers since there may be an awareness on increasing the usage of eco-friendly materials. However, the sustainability of natural fiber-reinforced polymer composites depends on several factors, including the type of natural fiber used, the type of polymer matrix, the processing techniques, and end-of-life disposal [31]. By choosing eco-friendly materials and processing techniques, and by implementing sustainable end-of-life strategies, natural fiber-reinforced polymer composites can be a sustainable alternative to traditional petroleum-based composites.

5.2 Economic Perspective of Natural Fiber Reinforced Polymer Composites

Natural fiber-reinforced polymer composites offer several economic benefits when compared to traditional petroleum-based composites. Some of these benefits include:

1. Cost: Natural fibers are readily available and often less expensive than synthetic fibers. This can result in a lower cost of raw materials and can make natural fiber-reinforced polymer composites more cost-effective than petroleum-based composites.
2. Reduced Processing Costs: Processing natural fibers requires less energy and fewer chemicals than processing synthetic fibers. This can lead to lower processing costs, making natural fiber-reinforced polymer composites more economically feasible.
3. Lightweight: Natural fiber-reinforced polymer composites are lightweight, which can lead to reduce transportation costs. This is particularly important in the automotive and aerospace industries, where weight reduction can lead to significant cost savings.
4. Reduced Tooling Costs: Natural fiber-reinforced polymer composites can be processed using conventional processing equipment, such as injection molding and compression molding. This can result in reduced tooling costs, making the production of natural fiber-reinforced polymer composites more economically viable.
5. Government Support: Many governments are providing incentives for the use of sustainable materials, including natural fiber-reinforced polymer composites. This can include tax credits, subsidies, and grants, which can make the use of these materials more financially attractive.

However, there are also some economic challenges associated with the use of natural fiber-reinforced polymer composites. These can include the initial investment required to develop new processing equipment, the requirement for specialized training for processing and design, and potential supply chain disruptions due to the limited availability of some natural fibers. It is important to carefully consider the upfront costs and potential challenges associated with using these materials.

5.3 The environmental perspective of Natural Fiber reinforced polymer composites

Natural fiber-reinforced polymer composites offer several environmental benefits when compared to traditional petroleum-based composites. Some of these benefits include:

1. Renewable and Biodegradable: Natural fibers are derived from renewable sources such as plants and

animals, and they can be easily decomposed by microorganisms in the soil. This makes them a sustainable alternative to synthetic fibers that are derived from non-renewable sources and can persist in the environment for a long time [32].

2. Reduced Carbon Footprint: Natural fibers have a lower carbon footprint than synthetic fibers, which are produced from petroleum. Additionally, the processing of natural fibers requires less energy and fewer chemicals, which can further reduce the carbon footprint of natural fiber reinforced polymer composites.
3. Reduced Waste: Natural fibers can be easily recycled or composted, reducing the amount of waste that ends up in landfills [33]. This is particularly important given the increasing concerns about the accumulation of non-biodegradable waste in the environment.
4. Reduced Toxicity: The processing of natural fibers typically involves the use of fewer toxic chemicals than the processing of synthetic fibers. This can lead to a reduction in the release of harmful chemicals into the environment.
5. Improved Air Quality: The use of natural fibers in composites can improve indoor air quality by reducing the emission of Volatile Organic Compounds (VOCs) that can be harmful to human health.

However, there are also some environmental challenges associated with the use of natural fiber reinforced polymer composites. These can include the potential for deforestation and habitat loss, as well as the energy and resources required for the cultivation and processing of natural fibers. The environmental perspective of natural fiber reinforced polymer composites is positive, with the potential to reduce waste, improve air quality, and lower the carbon footprint of composites. However, it is important to carefully consider the environmental impacts of the entire lifecycle of natural fiber reinforced polymer composites, from the cultivation of natural fibers to the end-of-life disposal by conducting a proper Life Cycle Assessment (LCA).

Natural Fiber Reinforced Polymer Composites (NFRPCs) can exhibit good mechanical properties such as strength and stiffness, but their properties can be further improved by various chemical treatments and other methods. Here are some common methods to improve the strength and stiffness of NFRPCs:

1. Chemical treatment: Chemical treatment is a widely used method to improve the adhesion between natural fibers and polymer matrix in NFRPCs. Common chemical treatments include alkali treatment, acetylation, silane coupling, and maleic anhydride grafting [34]. These treatments can modify the surface chemistry of the natural fibers, creating new chemical groups that can form strong chemical bonds with the polymer matrix, resulting in improved interfacial adhesion and mechanical properties.
2. Fiber modification: Natural fibers can be modified to improve their mechanical properties, such as by using mechanical or enzymatic methods to break down their structure and increase their aspect ratio. Fiber modification can improve fiber-matrix interaction, leading to improved mechanical properties of the composite.
3. Matrix modification: The polymer matrix can also be modified to improve the mechanical properties of NFRPCs. One example is adding nanoparticles to the matrix, such as clay or graphene, which can enhance the strength and stiffness of the matrix and improve the mechanical properties of the composite.
4. Hybridization: Hybridization involves combining different types of natural fibers or combining natural fibers with synthetic fibers to create a composite with improved mechanical properties. For example, combining bamboo fibers with kenaf fibers can create a composite with improved strength and stiffness.
5. Processing methods: The processing method used to create NFRPCs can also impact their mechanical properties. For example, using hot pressing or extrusion can improve the interfacial adhesion and

mechanical properties of NFRPCs compared to cold pressing.

Overall, these methods can be used to tailor the mechanical properties of NFRPCs for specific applications and improve their sustainability by reducing the need for synthetic materials. However, it is important to balance the properties and cost of the composite when selecting a method to improve the mechanical properties of NFRPCs.

5.4 Challenges associated with NFRPC materials

While Natural Fiber Reinforced Composites (NFRCs) offer many advantages over traditional materials, there are also challenges that must be addressed to fully realize their potential in various applications. Here are some of the challenges and future perspectives of NFRCs applications. There is a lack of standardization and certification for NFRCs, which makes it difficult for manufacturers and consumers to compare and evaluate the performance of different materials. Future development in this area may involve the establishment of standards and certification processes to ensure consistency and quality in NFRCs. Cost and scalability have become an important challenge because the cost of natural fibers and processing technologies for NFRCs can be higher than traditional materials. This can make it difficult for NFRCs to compete in price-sensitive markets. Future development in this area may involve the use of new natural fibers, improved processing technologies, and economies of scale to reduce the cost of NFRCs and make them more widely available. When considering the durability and aging, natural fibers may be susceptible to degradation over time due to environmental factors such as moisture, UV radiation, and temperature changes. This can directly affect the mechanical properties and performance of NFRCs. Future development in this area may involve the use of new natural fibers and improved processing techniques to create NFRCs with enhanced durability and resistance to aging. Recycling and disposal can be considered as a major challenge with increasing the usage of natural fibers. While NFRCs are more environmentally friendly than traditional materials, their end-of-life disposal remains a challenge. Future development in this area may involve the use of biodegradable natural fibers and the development of recycling and disposal technologies to reduce waste and environmental impact.

Despite these challenges, the future perspectives of NFRCs applications remain promising. Continued research and development in this field can help to overcome these challenges and unlock the full potential of NFRCs as sustainable and eco-friendly materials for various applications.

5.5 Future Perspectives of Natural Fiber Reinforced Composites

The future perspectives of Natural Fiber Reinforced Composites (NFRCs) are promising and offer many exciting opportunities for sustainable and eco-friendly materials in various industries. Here are some of the future perspectives of NFRCs. It’s very useful to pay significant attention for the development of new natural fibers since researchers are exploring new natural fibers for use in NFRCs, such as kenaf, bamboo, and flax. These fibers have unique properties and offer different advantages, such as improved strength and stiffness, higher impact resistance, and greater resistance to environmental degradation. Advances in processing techniques can also be done for NFRCs, such as hot pressing and injection molding, can help to improve the mechanical properties and reduce the production cost of these materials. These advances can also help to increase the scale of production and make NFRCs more widely available. Use in emerging applications is another perspective because NFRCs have potential for use in emerging applications, such as automotive and aerospace industries. These applications require materials with high strength-to-weight ratios and superior mechanical properties. NFRCs offer advantages over traditional materials such as steel and aluminum, including lower weight and greater sustainability. As well as the integration of NFRCs with new technologies such as additive manufacturing and 3D printing can help to create complex shapes and structures with improved mechanical properties. These technologies can also help to reduce material waste and increase the efficiency of production. The future perspectives of NFRCs offer exciting opportunities for sustainable and eco-friendly materials in various industries. Continued research and development in this field can help to unlock the full potential of NFRCs for emerging applications and address challenges such as standardization, cost, durability, and recycling.

6. Conclusion

Composite materials have emerged as vital components in modern industrial applications, with a particular focus on fiber-reinforced polymer composites (FRPCs) and natural fiber-reinforced polymer composites (NFRPCs). These materials possess unique properties that make them highly desirable, including their exceptional strength-to-weight ratios, remarkable durability, resistance to corrosion and fatigue, and versatile design capabilities. FRPCs, utilizing carbon, glass, or aramid fibers as reinforcement, have gained widespread acceptance in industries such as aerospace, automotive, construction, and marine due to their lightweight nature, high strength, and corrosion resistance. On the other hand, NFRPCs, employing natural fibers like jute, flax, hemp, and bamboo, offer added advantages, including biodegradability, sustainability and reduced environmental impact.

From an economic perspective, the utilization of natural fibers in these composites often results in cost savings, as they are generally less expensive than synthetic fibers. Furthermore, reduced processing costs, lightweight characteristics, and government support contribute to their economic viability. Nevertheless, challenges such as initial investment, specialized training requirements, and potential supply chain disruptions need to be addressed.

From an environmental standpoint, NFRPCs provide significant sustainability benefits owing to their renewable and biodegradable nature, reduced carbon footprint, and positive impact on air quality. Implementing recycling and appropriate end-of-life disposal techniques is essential to enhance their environmental performance. The development of biodegradable polymer matrices and the adoption of environmentally friendly processing methods further contribute to their overall sustainability.

Various methods, such as chemical treatments, fiber and matrix modifications, hybridization, and optimized processing techniques, can be employed to enhance the mechanical properties of NFRPCs. These approaches enable the tailoring of composite properties to suit specific industrial applications.

Despite challenges related to standardization, cost, durability, and recycling, the future outlook for NFRPCs is highly promising. Ongoing research and development endeavors are focused on exploring new natural fibers, advancing processing techniques, identifying emerging applications in sectors like automotive and aerospace, and integrating NFRCs with technologies such as additive manufacturing.

Composite materials, particularly FRPCs and NFRPCs, offer a wide array of benefits in terms of mechanical properties, economic feasibility, and environmental sustainability. Continued progress and innovation in these domains will further drive the widespread adoption of composite materials across diverse industries, paving the way for a more sustainable and eco-friendly future.

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