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Sustainable Composites in Mechanical Engineering

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Abstract
This review paper explores the development and application of sustainable fiber composites, focusing on their potential to replace conventional synthetic fiber composites in various industries. Natural fiber composites (NFCs) offer unique advantages, such as biodegradability, low cost, renewability, and lightweight properties, making them an environmentally friendly alternative. Unlike conventional composites, which often rely on non-renewable resources like glass and carbon fibers, NFCs are derived from natural sources, such as plants and animals, contributing to a reduced environmental footprint. This paper provides a comprehensive analysis of the properties, treatments, and applications of various natural fibers, including date palm, bamboo, jute, and hemp. Despite some challenges, such as moisture absorption and fiber/matrix compatibility, natural fiber composites offer a promising future due to their sustainable nature and the growing emphasis on green technologies. The potential benefits of NFCs extend beyond environmental impact, offering economic and societal advantages by supporting sustainable development and efficient waste management practices. This review underscores the importance of continued research and development in the field of natural fiber composites, which are poised to play a pivotal role in creating a more sustainable and resilient future.

Introduction

Composite Materials

One definition of a composite material describes it as being made of two constituents: fiber (the reinforcement) and glue (the matrix). This combination results in properties superior to those of the individual components when used separately. Composite materials have significant advantages over traditional materials like metals or plastics, including high strength and stiffness combined with low density, which facilitates weight reduction in the final product.

The current use of composite materials is primarily driven by the aerospace sector. A significant portion of modern airplane structures, such as the Boeing 787 and Airbus A380, are manufactured using carbon, glass, and aramid fibers.

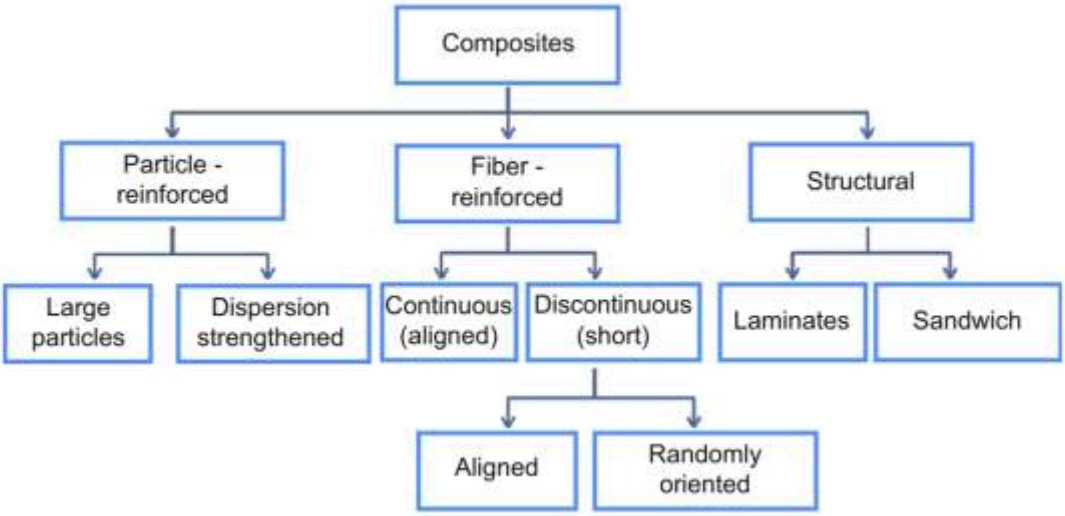
In polymer matrix composites (PMCs), the polymer matrix, which has low strength and stiffness, plays essential roles in maintaining fiber orientation and spacing, protecting fibers from environmental damage, and transmitting external loads to the fibers through shear loading at the interface. The matrix ensures a strong bond with the reinforcement, enabling effective load transfer. There are two main types of polymer matrices: thermosets, which start as low-viscosity resins that cure into solids during processing and cannot be reshaped once set, and thermoplastics, which are high-viscosity resins that can be repeatedly melted, reshaped, and solidified [1].

Sustainable composites

In polymer composites, plastic resins form the continuous phase, while fibers and fillers remain in the discontinuous phase to provide reinforcement. The composite's performance is primarily governed by the interface between the fibers and the polymer matrix, as the stress transfer between them dictates the overall mechanical properties. In composite science, focusing on the interface and the related interfacial bonding is crucial for optimizing performance. When selecting fibers and fillers for sustainable composite applications in industrial sectors, it is essential to compare the cost, availability, property consistency, and environmental benefits of sustainable fibers with traditional synthetic options [1,2].

In the automobile industry, significant amounts of composites are used in the production of hybrid electric cars and batteries for electric vehicles, enhancing mass reduction and driving range. Similarly, sports cars and supercars utilize polymer composites to improve performance and reduce emissions to acceptable standards. These high-tech cars benefit from the advanced properties of polymer composites. Additionally, natural fiber polymer composites are used in the transportation industry for interior trim panels and bins in family cars, storage systems for pickups and vans, large panels on commercial buses, cabs for medium and heavy-duty trucks, and energy-absorbing composite crash elements [2].

Figure 1. Composite Material [1]



Polymer composite materials offer significant advantages over steel in the automobile and transportation industries. These include a 20-40% reduction in weight, increased styling flexibility of deep-drawn panels reducing the need for steel metal stamps, and a 40-60% reduction in tooling costs. Additionally, there is an overall cost reduction in assembly with more efficient part consolidation. Polymer composites provide strong resistance to rust, scratches, and indentations, reduce noise, vibration, and harshness, and offer higher damping. They also enable new process innovations that add value to the final product while providing cost savings and enhancing safety due to their higher specific energy absorption [1].

The idea of utilizing natural fiber-reinforced composites for automotive applications dates back to the 1940s when Henry Ford experimented with soya beans to produce these composites. Although his idea did not gain traction at the time due to the reliance on cheap petroleum, it indicated a preference for a new generation of biocomposites for automobile applications. This early innovation paved the way for the current utilization of biocomposites in designing and fabricating various vehicle components in Europe and North America. Presently, many major automotive manufacturers, including Daimler Chrysler, Mitsubishi, General Motors, Volkswagen, Ford, Toyota, and BMW, have incorporated natural fiber-reinforced composites in the design of their vehicles' interior and exterior components.

The most common components made with biocomposites include dashboards, headliners, seat backs, door panels, trunk liners, package trays, and other interior trim parts. In Europe, Chrysler has been particularly successful in developing vehicle components using biocomposites, as demonstrated in its latest Mercedes-Benz brand. On the other hand, Fiat has utilized fuel lines made of castor oil-derived nylon in several of its vehicle models. In North America, Ford used wheat straw-reinforced materials to fabricate the storage bin and inner lid of its 2010 Flex crossover vehicle, and cellulose fiber-reinforced thermoplastic for its 2014 Lincoln MKX models. Ford now incorporates soy-based foam seating in all its North American car models and uses kenaf-reinforced PP composites in the interior door panels of the Mondeo, Focus, and Fiesta models.

General Motors has used flax-reinforced PP composites for the design of rear shelf components in the Chevrolet Impala model. A mixture of kenaf and flax fiber has been utilized in package trays and door panel inserts for the Saturn L300 and the European-market Opel Vectra. Additionally, wood fibers are used in the backseats of the Cadillac Deville and Chevrolet TrailBlazer.In 2011, Toyota developed a new bio-based polyethylene terephthalate (PET) from sugarcane and used it to fabricate component material in the luggage compartment liner of its Lexus CT200h hybrid-electric compact model car. Other Asian auto companies have also embraced biocomposites: Mitsubishi developed a new automobile floor mat using bio-PE manufactured from sugarcane molasses and PP fiber, while Honda uses wood fiber in the fabrication of floor area parts for the Pilot SUV model car [2,3].

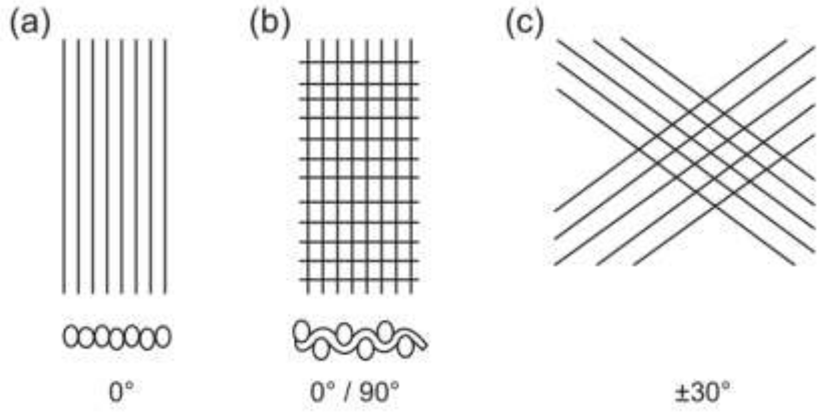


Figure 2. (a) unidirectional fiber, (b) woven cloth, bi directional, (c) filament winding

Bast Fibers

Bast fibers, which are potential sustainable fibers, are produced from the outer layers of plant stems and are primarily composed of cellulose, hemi-cellulose, and varying proportions of lignin. The most valuable fiber crops that have gained interest as reinforcements for composites include jute, flax, ramie, hemp, and kenaf.

Jute Fibers

Popularly known as the “Golden Fiber,” jute is extracted from the bark of the white jute plant (Corchorus capsularis) and is a 100% biodegradable, recyclable, and environmentally friendly natural fiber. After cotton, jute is the second most produced natural fiber globally, primarily in developing countries such as Bangladesh, India, and China. Jute is a lignocellulosic fiber and is approximately 50% cheaper than flax and other similar natural fibers. Jute plants can grow up to 15–20 cm in four months, and the fibers are extracted post-harvesting. These fibers are characterized by a high aspect ratio (length-to-diameter ratio, l/d), high strength-to-weight ratio, and good insulation properties.

Flax Fibers

The cloth made from flax fibers is popularly known as "linen" in the textile industry. Flax fibers are cellulosic but have higher crystallinity compared to jute fibers. The technical fibers extracted from the plant can be very long (up to 90 cm) with a diameter of 12–16 µm. France, Belgium, and the Netherlands are the leading manufacturers of flax fibers. Flax fibers possess higher specific tensile properties than glass fibers, along with low density, higher strength, and stiffness. This higher strength makes them attractive for composite applications. Extensive studies have investigated flax as reinforcing materials in the form of non-woven mats, combined with natural resin, to develop sustainable composites for the future [3].

Ramie

Ramie is a strong, lustrous, soft, and fine bast fiber extracted from the inner bark of the ramie plant. It is one of the oldest vegetable fibers, historically used to wrap mummies in Egypt. China is the leading producer of ramie fiber. A significant challenge with ramie processing is removing its gum content, which constitutes about 30% of the total fiber weight, making it difficult to spin. However, this extracted gum can sometimes be used as a natural resin to develop green particle boards or other biocomposites. Ramie is often used in manufacturing fishing nets, ropes, tents, household furnishings, and composites.

Hemp

Hemp, most widely grown in Asia and Europe, can grow up to approximately 1.2–4.5 meters with plant stems around 2 cm in diameter. The inner girth is usually covered by a core, while the outer layer consists of bast fiber attached via a glue-like substance called pectin. Hemp fibers possess excellent mechanical strength and Young’s modulus, as well as good insulation properties. These fibers are generally used in ropes and mulching and have found applications as reinforcement in composites.

Kenaf

Kenaf is a strong, stiff, and tough bast fiber with high resistance to insects. It is primarily extracted from the plant's flowers, consisting of an outer fiber known as the bast, which makes up 40% of the stalks' dry weight, and an inner core. Kenaf fibers are characterized by low density, high specific mechanical properties, and complete biodegradability. Traditionally used for making cords, ropes, and storage bags, kenaf has recently found applications as composite reinforcements in automobiles, construction, furniture, and packaging [3].

Leaf Fibers

Using lignocellulosic leaf fibers, such as sisal, pineapple, and banana, as reinforcements in thermoplastic and thermosetting resins to develop low-cost and lightweight composites is an emerging field of research. These fibers offer several advantages, including low density, low cost, non-abrasive nature, low energy consumption, high specific properties, and biodegradability.

Sisal

Sisal, which originates from Mexico, is among the most commonly used leaf fibers. It comes from the rosette of leaves that can reach a height of 1.5 to 2 meters. Sisal fiber is easy to cultivate and has short renewal times. It boasts high tenacity and tensile strength, along with resistance to abrasion, saltwater, acids, and alkalis. Initially, sisal was used to make ropes and twines. More recently, it has found applications as a reinforcement in composite materials and in furniture [2,3]

Pineapple Leaf Fiber

Pineapple leaf fiber, a byproduct of fruit cultivation, is a white, creamy, and lustrous material resembling silk but is ten times coarser than cotton fiber. This multi-cellular lignocellulosic fiber exhibits excellent mechanical, physical, and thermal properties. Major applications for pineapple leaf fiber include its use in automobiles, mats, construction, and advanced composite materials [3]

Banana Fiber

Banana fiber, also known as "Musa fiber," is one of the world's strongest natural fibers. It is biodegradable and extracted from the pseudostem of the banana tree, which is highly durable. The fiber is made up of thick-walled cell tissue bonded by natural gums, primarily composed of cellulose, hemicellulose, and lignin. While banana fibers are often compared to natural bamboo fibers, they possess superior fineness, spinability, and tensile strength. Different types of textiles with various thicknesses and weights can be produced from banana fibers, depending on the part of the banana stem they are extracted from. Banana fibers can be used to make ropes, mats, woven fabrics, and handmade papers. Additionally, they are used as reinforcement materials in the manufacturing of green composites [2].

Bamboo Fiber

Bamboo fibers, also known as natural glass fibers due to their longitudinal fiber alignment, are extracted from natural bamboo trees using various physical and mechanical methods. These fibers have garnered interest because of their high aspect ratios and high strength-to-weight ratios. Additionally, bamboo fibers have a smooth, round surface. They are lighter, stiffer, and stronger than glass fibers, making them attractive reinforcement materials for manufacturing advanced composite materials across various industries.

Fruit Fibers

The fruits and seeds of plants are often surrounded by hairs or fibers, or encased in a fibrous husk. These fibers, composed of cellulose and lignin, are known for their durability and thermal insulation properties. They hold significant potential as reinforcement materials for composite applications.

Coir

Coir is a short, coarse fiber extracted from the outer shell of coconuts. Compared to other natural fibers, coir has a much greater thickness and exhibits excellent chemical resistance. Its slow decomposition rate makes coir suitable for producing durable geotextiles. There are two types of coir: coarser brown coir and finer white coir. Brown coir, obtained from mature coconuts, is more commonly used. Coir fibers are primarily utilized in the production of rugs, mattresses, doormats, building boards, insulation boards, cement boards, building panels, and composites.

Kapok

Kapok fibers, derived from the seed hairs of kapok trees, resemble cotton and range in color from yellowish to light brown. These fibers are extremely lightweight and hydrophobic. Traditionally, kapok fibers are used as buoyancy materials, oil absorbents, biofuels, insulation materials for heat and sound, and reinforcement materials for composites [3]

Palm

Palm fibers are typically obtained from the fruits, rachis, and leaves of date palm trees. These fibers can serve as valuable sources of cellulose and lignin. In the automotive sector, palm fibers have potential applications as reinforcements for thermoplastic and thermosetting polymer-based composites.

Agro waste fibers

Primary fiber wastes generated from agricultural activities are a rich source of cellulose. These wastes have significant potential as reinforcing materials due to their abundance and the advantages of being renewable, degradable, and cost-effective. Such biomass wastes offer excellent specific properties, particularly mechanical, thermal, and biodegradability, making them ideal for use as reinforcements in FRP composite applications [3]

Sugarcane bagase

Sugarcane bagasse is a fibrous material obtained as a residue from sugarcane after crushing to extract the juice. It consists mainly of two components: the outer rind and the inner pith. The rind has a strong fibrous structure that protects the softer, spongy inner components. It contains long, fine fibers that are randomly arranged throughout the stem and bonded together by hemicellulose and lignin. The inner component has smaller fibers, primarily composed of cellulose. Sugarcane bagasse is approximately 50% cellulose, 25% hemicellulose, and 25% lignin. Its high cellulose content, which exhibits a highly crystalline structure, makes it an excellent composite reinforcement material. Bagasse is widely used in applications such as cement composites, false ceilings, particle boards, and lightweight structures [3].

Corn Stalk

Corn stalks consist of both a pith and a rind. The pith is rich in hemicellulose, fat, protein, and sugar, whereas the rind primarily contains cellulose and lignin, which contribute to its high strength and toughness. Due to the weakly bonded pith, corn stalks can exhibit poor strength, making it necessary to remove the pith when preparing corn stalk fibers. The rind of corn stalks is used to manufacture corn stalk fiber-based composite materials [2].

Rice straw

Rice straws (RS) are non-wood bio-fibers obtained as a residue from rice production. Major rice-producing countries like Vietnam, India, and Bangladesh generate a substantial quantity of rice residues after husking. Traditionally, these residues are either used as animal feed or disposed of by burning in the fields, which contributes to carbon emissions. However, using these residues as reinforcement materials in polymer composites can help reduce environmental pollution and find valuable applications in composite reinforcement [2,3]

Challenges in implementing sustainable composites in Automobile and Aircraft industry

Water absorption

One of the primary issues with natural fiber-reinforced polymers (FRP) is their high moisture absorption. The mechanical properties of FRP are significantly influenced by the adhesion at the fiber-matrix interface. Fibers are known to be rich in cellulose, hemicellulose, lignin, and pectins, all of which contain hydroxyl groups, making them highly polar. In contrast, most polymers are quite hydrophobic. The water absorption of a fiber-reinforced composite depends on the absorption characteristics of both the fiber and the polymer matrix. Typically, high water intake in composite materials can lead to pressure on nearby structures, swelling, increased deflection, a potential decrease in strength, and increased weight of the wet profiles. Excessive water absorption in a composite also provides a conducive environment for microbial attack.

Flame Retardancy

The use of natural fibers in applications has been restricted due to their poor flame resistance. Extensive research has been conducted to enhance the flame retardancy of natural fiber-reinforced polymer (FRP) composites. Natural polymers and fibers are organic materials that are highly susceptible to fire. When exposed to flames, the burning process of composite materials occurs in five sequential stages: heating, ignition, combustion, decomposition, and propagation. The combustion of these composites primarily produces two types of byproducts, depending on their cellulose and lignin content. High cellulose content leads to increased flammability, while high lignin content is associated with a higher likelihood of char formation.

Literature Review

Amar k. Mohanty et al. (2018). Interest in creating composite materials from biosourced, recycled materials and waste resources, as well as their combinations, is increasing. Biocomposites have caught the attention of automakers for designing lightweight parts. Technological advances in manufacturing have been made through hybrid biocomposites composed of petrochemical-based and bioresourced materials. Greener biocomposites, made from plant-derived fibers and crop-derived plastics with higher biobased content, are continually being developed. Biodegradable composites show significant potential for use in sustainable packaging. Recycled plastic materials, originally destined for landfills, can be redirected and repurposed for blending in composite applications, reducing reliance on virgin petro-based materials. Research on the compatibility of recycled and waste materials with other components in composite structures to improve interface and mechanical performance presents major scientific challenges. This research holds the promise of advancing a key global sustainability goal [1].

Adamu Muhammad et al. (2021). Due to rising fuel costs for commercial aircraft, there is a growing need to increase research focused on achieving environmental sustainability within the aeronautic industry. This industry faces significant pressure to enhance performance, particularly in the area of weight reduction. Simplifying day-to-day aircraft maintenance is essential to reduce component usage and lower operating costs. In the near future, aircraft design and construction may significantly cut operating costs through the careful selection of polymer composite materials with excellent mechanical and physical properties. Currently, there is competition not only in the realm of airplanes but also in missiles. Composite technology continues to advance, with the introduction of new materials such as basalt and carbon nanotube forms aimed at accelerating and expanding the use of composites [2].

Saptarshi Maiti et al. (2022). Sustainable fiber-reinforced polymer (FRP) composites, made from renewable and biodegradable fibrous materials and polymer matrices, are of significant interest due to their potential to reduce environmental impacts. However, these composites still fall short of the high-performance standards set by conventional glass or carbon FRP composites. Therefore, achieving a balance between performance and biodegradability is essential to develop eco-friendly composites. This review offers an overview of sustainable FRP composites, including their manufacturing techniques and overall sustainability at the materials, manufacturing, and end-of-life stages. It summarizes sustainable plant-based natural fibers and polymer matrices, along with their modification techniques to create high-performance, multifunctional, and sustainable FRP composites. The current state-of-the-art mechanical and functional properties of these composites are examined, as well as their potential applications in various industries, including automotive, aerospace, construction, medical, sports, and electronics. Lastly, future market trends, current challenges, and perspectives on the future of sustainable natural FRP composites are discussed [3].

Yasir Khalid et al. (2021). In today's world, natural fiber-reinforced polymer composites (NFRPCs) are gaining significant attention due to their eco-friendly properties, light weight, life-cycle advantages, biodegradability, low cost, and excellent mechanical properties. NFRPCs are increasingly used in various engineering applications, and the field is continually evolving. However, researchers encounter numerous challenges in the development and application of NFRPCs because of the inherent characteristics of natural fibers (NFs). These challenges include the quality of the fiber, thermal stability, water absorption capacity, and incompatibility with polymer matrices. Ecological and economic concerns are driving new research in the field of NFRPCs. Additionally, significant research has been conducted in recent years to enhance the performance of NFRPCs. This review emphasizes key advancements in NFRPCs in terms of sustainability, eco-friendliness, and economic considerations. It also covers the hybridization of natural fibers with synthetic fibers, which effectively improves the mechanical properties of NFRPCs, along with various chemical treatment processes. Furthermore, this review highlights the importance of using numerical models for NFRPCs. Lastly, conclusions and recommendations are provided to guide researchers in future research directions [4].

Yuqi Feng et al. (2024). Due to the global focus on sustainable development, natural fiber composites (NFCs) have become increasingly appealing for their impressive performance, unique functionality, and eco-friendliness. Natural fibers are biodegradable, affordable, and low-density, making them promising materials for developing alternatives to traditional petroleum-based synthetic fiber composites. However, issues such as poor compatibility between natural fibers and the matrix pose challenges to the further advancement of NFCs. Research has shown that molecular dynamics (MD) simulations can provide valuable insights into the fundamental properties and deformation mechanisms that influence the macroscopic performance of NFCs, including mechanical properties, thermal stability, and interfacial interactions. By understanding the nanostructure of natural fibers, it is possible to modify these fibers at the nanoscale to enhance the performance of NFCs. This paper begins by reviewing the hierarchical structures of natural fibers, primarily wood and bamboo fibers, and their relationship to mechanical and thermal properties. It then discusses treatments to improve the compatibility between natural fibers and the matrix. The key factors behind the functional properties of modified NFCs are explored at the nanoscale. Additionally, the paper reviews the applications of NFCs as structural and functional materials in the construction, automotive, and aerospace industries. Finally, it highlights the increasing use of machine learning-assisted MD simulation techniques to aid in the design of NFCs. The literature and data for this study were sourced from a combination of online academic databases, citation chaining, government databases, and industry reports [5].

Rittin Abraham et al. (2023). As synthetic fibers have long contributed to environmental pollution, researchers are actively seeking more eco-friendly alternatives, such as natural fibers. Natural fibers, derived from plants and animals, include options like bamboo, hemp, jute, and oil palm, which have the potential to replace synthetic fibers in the production of biodegradable and lightweight composites with enhanced mechanical properties. These properties can be further improved through specific chemical modifications. Additionally, the morphology of these fibers can be altered using various chemical treatments to promote better mechanical interlocking. This review discusses the properties of natural fibers such as jute, bamboo, oil palm, and hemp, along with the latest potential applications aimed at fostering sustainability and commercial value. The creation of green composites from natural fibers is a promising field, with applications extending to 3D and 4D printing also being highlighted. Through this paper, we analyze the significance of selecting sustainable solutions like natural fibers over non-biodegradable synthetic fibers, which pose unavoidable environmental hazards. To advance environmentally friendly products and replace synthetic fibers with effective and affordable alternatives, this study explores the diverse properties and latest potential applications of natural fibers across various commercial industries. This demonstrates that natural fibers, as a non-polluting, safe, renewable, and legitimate fiber source, will likely be extensively used in composite manufacturing in the coming years [6].

Yashas Gowda et al. (2019). The growing awareness of the environmental damage caused by synthetic materials has sparked the development of eco-friendly alternatives. Researchers have shown significant interest in creating materials that can replace synthetic ones. Consequently, there has been an increased demand for the commercial use of natural fiber-based composites across various industrial sectors in recent years. Natural fibers are sustainable materials readily available in nature and offer benefits such as low cost, light weight, renewability, biodegradability, and high specific properties. The sustainability of these natural fiber-based composite materials has led to their expanded applications in multiple manufacturing sectors. This paper reviews the different sources of natural fibers, their properties, methods for modifying them, and the effects of various treatments. Additionally, it summarizes the major applications of natural fibers and their effective use as reinforcement in polymer composite materials [7].

Jefferson Andrew (2021). The increasing awareness of environmental and sustainability issues has driven the development of biobased composite materials as innovative alternatives to conventional non-renewable synthetic fibers like glass and carbon-reinforced composites. However, biocomposite materials are not without their challenges, including poor moisture resistance (hydrophilicity), fiber/matrix incompatibility, supply chain logistics, low thermal stability, flammability, poor electrical properties, and issues related to extraction, processing, surface modification, machining, manufacturing, and characterization. They also exhibit highly anisotropic properties. Recently, extensive research has been conducted to address these challenges, focusing on long-term durability, reliability, serviceability, and sustainable production through the adoption of a circular economy approach in biocomposites.

This article provides a critical review of recent research on various aspects of biocomposites. It begins with an overview of the general characteristics, including the extraction, chemical composition, and physical and mechanical properties of the most widely used biopolymers and biofibers (from both natural and synthetic sources) for fabricating biocomposites. The review also covers the approaches and advancements in enhancing the properties of biocomposites, such as fiber treatment and modification, fiber hybridization, incorporation of fillers, advanced manufacturing techniques, and exploration of new biofiber and polymer resources. Furthermore, it discusses the current techniques and developments in biocomposite manufacturing, with a focus on additive manufacturing (AM) techniques, particularly fused filament fabrication (FFF), to meet the demands for lightweight composites [8].

Guravtar Singh Mann et al. (2023). Global climate change is already impacting the environment, with glaciers receding, ice on rivers and lakes melting, plant and animal ranges shifting, and trees blooming earlier. Consequently, there has been a growing emphasis on sustainable materials. The demand for materials with unique properties that metals, polymers, and other traditional materials cannot provide has led scientists to focus on green composites. Green composites have a wide range of applications in the automotive, aerospace, and marine industries. These composites are multiphase materials composed of chemically distinct components with separate interfaces, providing a set of desirable features superior to those of their individual components.

Natural fibers, which are used in green composites, offer several advantages: they are less expensive, more readily available, rust-resistant, abundant, nontoxic, and safe for human skin, eyes, and respiratory systems. Green composites are formed by combining renewable fibers with polymers (matrix), creating a new class of materials known as "green composites." This review covers studies on various animal-based fibers and their applications, along with recent advancements in these fibers and their composites. The paper also discusses the physical, chemical, and mechanical properties of these materials, as well as the benefits and drawbacks of using them.

Finally, the paper provides an overview of the topic, presenting the results from composites made from each type of fiber and offering appropriate references for further in-depth studies. This review aims to enhance the knowledge base of young researchers working in the field of natural composites [9].

Faris Oqla (2013). Proper utilization of available natural resources and waste materials has become essential for achieving sustainability in industry. This study explores the feasibility of using date palm fibers (DPF) in natural fiber-reinforced polymer composites (NFCs) for the automotive industry. Additionally, it identifies a gap in the evaluation of NFCs based on comprehensive criteria, leading to the oversight of potential natural fiber types in industrial applications, relegating them to merely being an environmental waste issue.

In this work, criteria affecting NFCs were categorized and classified into different levels. Key criteria were proposed, collected, and tabulated according to each level. To demonstrate the potential and competitiveness of DPF in enhancing the sustainability of the automotive industry, various comparisons were made between DPF and other commonly used fiber types. In most comparisons, DPF emerged as the best choice, particularly regarding the specific Young's modulus to cost ratio criterion.

The study highlights that technical properties, performance, environmental, economic, and societal factors strongly support the adoption of DPF in the automotive sector. This adoption is shown to significantly enhance sustainability and productivity in the industry. Furthermore, utilizing DPF contributes to efficient sustainable waste management practices, thereby having a positive environmental impact [10].

Conclusion

The increasing awareness of environmental issues and the need for sustainable solutions have propelled the development and application of natural fiber composites (NFCs) across various industries. These composites, made from renewable natural fibers and polymers, offer a range of benefits, including biodegradability, low cost, light weight, and excellent mechanical properties. The exploration of fibers such as date palm, bamboo, jute, hemp, and others has shown promising potential in replacing synthetic fibers, particularly in sectors like automotive, aerospace, and construction. Despite challenges such as fiber/matrix compatibility and moisture resistance, advancements in chemical treatments, fiber hybridization, and manufacturing techniques have significantly improved the properties and durability of NFCs. The integration of sustainable fibers not only enhances product performance but also supports environmental sustainability by reducing reliance on non-renewable resources and promoting efficient waste management. As research and technology continue to evolve, the adoption of natural fiber composites is poised to play a crucial role in creating a more sustainable and environmentally friendly future.

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