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Eco-Friendly Reinforcements in Polymer Composites: A Comprehensive Review for high performance composite and Sustainable Future

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ABSTRACT

The increasing demand for sustainable, resource-efficient materials has accelerated the development of eco-friendly reinforcement polymer composites, promising alternatives to traditional synthetic reinforcements. This review provides a critical evaluation of natural fiber- and particle-reinforced polymer composites derived from plant, animal, mineral, and waste sources. Particular emphasis is placed on the impact of the type of reinforcement material, the interfacial bond strength between the reinforcement and the polymer matrix, and surface treatment strategies on the mechanical, thermal, acoustic, and environmental properties of the composites. The advantages and limitations of various types of environmentally friendly reinforcements are systematically compared, highlighting the balance between performance, durability, manufacturability, and sustainability. Furthermore, traditional and advanced manufacturing techniques are reviewed and evaluated, including compression molding, resin transfer molding, injection molding, vacuum-assisted processes, and 3D printing. This review also discusses life cycle assessment (LCA), recyclability, circular economy principles, and sustainability indicators that support the environmental benefits of environmentally friendly composites. Current applications are also reviewed. The study identified the key challenges related to moisture sensitivity, long-term durability, and the variability of natural material properties. It also proposed future research directions to support the industrial-scale expansion of sustainable composite material systems.

1. Introduction

Modern engineering systems require the creation of polymer-based materials that possess distinct physical characteristics, including mechanical strength and deformation resistance, electrical properties, elastic behavior, and thermophysical performance, which cannot be achieved with standard single-material systems [1, 2]. Engineers design polymer composite materials to achieve specific mechanical, thermal, electrical, and functional attributes through material design methods [3]. Polymers offer design flexibility, low density, and simple processing advantages, but they face several challenges, including limited-service temperatures, reduced hardness, and low stiffness. The use of these materials is limited because their drawbacks prevent their application in engineering projects that require high temperatures and load-bearing capacity when used without reinforcement [4, 5]. The properties of polymer composites can be effectively controlled by modifying the composite composition and processing conditions, particularly by selecting the reinforcement type, volume fraction, orientation, and distribution. The performance of these composites changes significantly with minor adjustments to reinforcement parameters [2] . In addition, the interfacial

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bonding quality between the matrix and reinforcement materials determines how well the composite transfers mechanical loads between its two components [3, 6].

The selection of materials nowadays emphasizes sustainability as the main determining factor. The growing awareness about how human activities harm the environment, together with the need to protect material performance and environmental resources through recyclable products, has become an essential requirement for engineers who design products and develop materials [5, 7]. Eco-friendly, reinforced polymer composites are effective alternatives for sound-absorbing applications because they maintain low weight and complete biodegradability while exhibiting strong mechanical and acoustic performance. The reinforcement type determines the fiber classification in polymer composites, which includes synthetic fibers, such as carbon and glass, that provide high stiffness and strength, and natural fibers, such as jute, flax, bamboo, kenaf, and luffa, that are renewable, cost-effective, and environmentally sustainable [8, 9]. Furthermore, natural fibers are environmentally friendly because they maintain specific strength while exhibiting low density and good stiffness when used in polymer matrices; thus, they are suitable replacements for glass and carbon fibers in non-structural and semi-structural applications. It was found that using natural fibers helps reduce environmental damage through two main benefits: their production requires less energy, and they decompose after their useful life, generating fewer greenhouse gas emissions than synthetic fiber composites [11, 12]. Thus, the automotive industry, construction sector, and interior design field increasingly adopt these materials because they provide environmentally friendly solutions to replace traditional synthetic composite materials [8, 13]. Natural fibers are a rising reinforcement used for automotive composite components to replace conventional glass-fiber composites [14]. These benefits extend to several areas, including cost savings, good thermal insulation, good sound insulation, good product accessibility, good carbon dioxide absorption, good energy recovery, reduced breathing discomfort, reduced equipment deterioration, reduced skin discomfort, etc. [15]. The strength of these composites also depends on the fiber/matrix interaction, the compatibility and competitiveness of the reinforcement with the polymer resin, and the fiber–matrix interfacial adhesion. The integration of natural fibers such as flax, jute, and hemp has emerged as a sustainable alternative to synthetic fibers, improving biodegradability while maintaining mechanical strength [11]. It is emphasized that the use of natural fibers such as jute, hemp, bamboo, and oil palm promotes sustainable development and reduces the global carbon footprint [18]. Kangishwar et al. (2023) presented a comprehensive review of polymer composites (PMCs). The review emphasized growing environmental concerns associated with synthetic fiber reinforcements, thereby encouraging further research on bio-composites and eco-friendly natural fiber-reinforced polymers as sustainable alternatives [16, 17].

Natural fiber composites offer a sustainable, eco-friendly alternative to synthetic acoustic materials in the automotive, construction, and interior design industries. By combining renewable, porous fibers (such as bamboo, kenaf, hemp, and even chicken feathers) with viscoelastic polymer matrices, these materials effectively dissipate sound waves by converting them into thermal energy. Experimental data show that these composites are particularly efficient in the medium-to-high-frequency range (500–6300 Hz). Beyond their technical performance, using agricultural by-products like sugarcane bagasse and date palm fibers provides significant environmental benefits and boosts local economies. Current research is now focused on overcoming the final industrial hurdles: improving durability, ensuring fire retardancy, and establishing standardized testing protocols.[19]. Natural fillers, which include cellulose-based particles, agro-residue powders, and bio-derived particulates, improve polymer matrix performance by increasing stiffness, dimensional stability, and interfacial adhesion (Thakur & Thakur, 2014) [6]. Sustainable composite research demonstrates that natural particulate materials strengthen the matrix structure while reducing environmental impacts and manufacturing energy costs (Ashby, 2012) [5]. The present study establishes their biomedical and structural application value, showing that they perform as well as standard filler materials (Ali et al., 2025) [7]. Reviews of green and natural fiber/particle composites confirm that these materials provide lightweight, recyclable, and

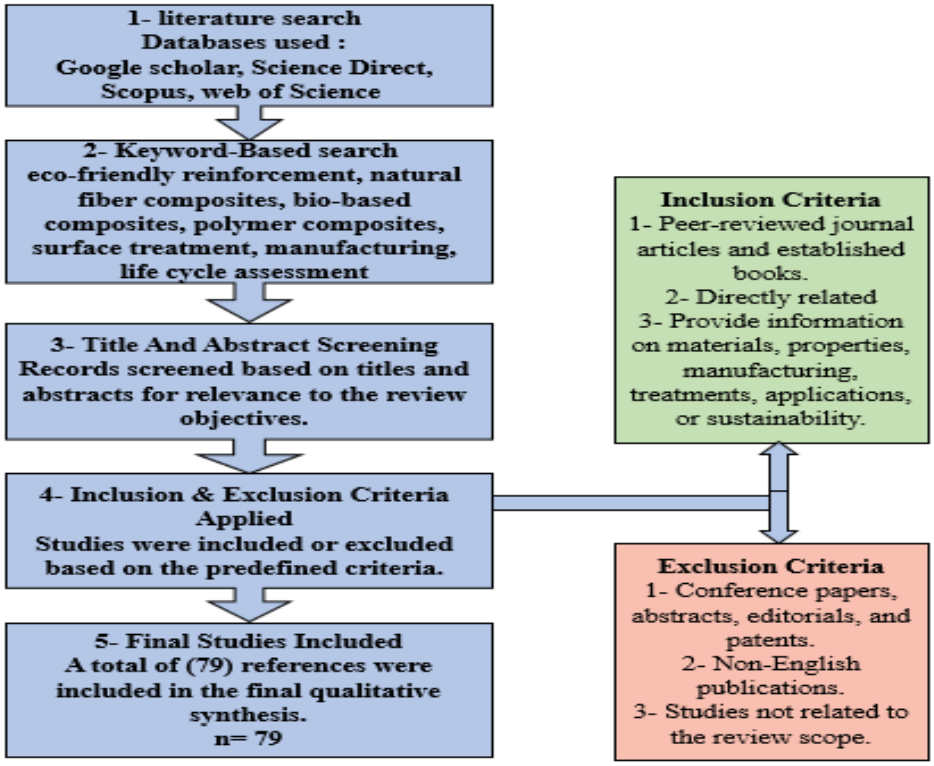


Figure 1 Flowchart of the literature search and study selection methodology.

environmentally friendly solutions for the automotive, construction, and consumer product industries (Pickering et al., 2016 [8]; Koronis et al., 2013 [9]).

The aim of this review is to investigate how eco-friendly reinforcement materials from natural fibers like flax, hemp, jute, kenaf, and other bio-based materials function as a sustainable replacement for traditional synthetic materials used in polymer composites. The study focuses on how natural materials affect polymer composite systems by demonstrating their ability to reduce environmental damage, lower processing energy requirements, and improve material compostability and recycling potential. The study evaluates the performance and sustainability of natural waste fiber- and particle-reinforced polymer composites and examines their current and future market applications in the construction, transportation, mobility, packaging, and insulation industries. The review demonstrates how natural reinforcements enable designers to create environmentally sustainable materials that meet essential performance standards.

2.Review Methodology

All sources used in this study were compiled from published research in recognized academic databases, including Google Scholar, ScienceDirect, and Scopus. These sources were limited to scientific research and books directly related to natural reinforced materials used in polymer composites, environmental sustainability, and repeatable life cycles. Ultimately, 79 sources were selected based on their titles and abstracts, and only after meeting the study's topic criteria, providing a comprehensive overview of this study as shown in Figure 1.

3. Evolution of Eco-Friendly Fiber Reinforced Polymer Composites (EFFRPCs)

The environmental problems caused by synthetic fibers, including carbon and glass materials, have prompted people to investigate eco-friendly alternatives. Therefore, people are increasingly choosing natural fibers, including animal-based materials such as wool and plant-based materials such as jute, flax, cotton, bamboo, abaca, and coir, to create biocomposites because these materials are renewable, biodegradable, and environmentally friendly [24]. Moreover, their extensive use is attributed to their renewability and biodegradability, low cost, wide availability, non-toxicity, low density, recyclability, and high strength-to-weight ratio. The role of eco-friendly fibers in enhancing the sustainability and mechanical performance of polymer composites is illustrated in Figure 2.

Compared to synthetic fibers, eco-friendly fibers offer better mechanical performance, resulting in lower environmental damage. Their production requires less energy and results in lower carbon emissions, supporting sustainability. The advantages of bio-composites have created growing interest in their use in structural and semi-structural applications [8]. Kamarudin et al. reviewed the mechanical and physical properties of plant fiber-reinforced polymer composites, and they demonstrated that plant fibers' low density enhances specific stiffness and strength, making them suitable for lightweight designs. In addition, plant fibers provide good damping and aacoustic insulation properties, particularly for automotive and building applications [42]. Akhil et al. found that plant fibres are prone to moisture absorption, leading to swelling, degradation of the fibre–matrix interface, and deterioration of long-term mechanical

properties. Variability between batches and regions, limited high-temperature processing capability, and lower absolute strength than glass or carbon fibres restrict their structural applications unless hybrid designs are employed [43]. Yan et al. showed that flax fibers, which come from the stems of the flax plant, exhibit strong tensile strength and high stiffness. Flax fibers have gained popularity in high-performance applications, including automotive composites and sporting goods, for their outstanding mechanical properties [20]. Whilst hemp fibers, which people obtain from the stems of the hemp plant, possess strong durability and pest and mildew resistance, together with a high fiber yield. Hemp fibers are suitable for multiple applications, including construction materials, textiles, and automotive components [21]. Also, kenaf fiber comes from a rapidly growing plant and produces strong, high-stiffness fibers. Kenaf fibers possess distinct features that make them suitable for use in paper production, construction materials, and automotive composite applications [22]. Previous studies have also indicated that abaca exhibits high tensile strength, jute has a high Young's modulus, and silk offers excellent elongation at break. Natural fiber selection depends primarily on biodegradability, as this property helps reduce both environmental contamination and waste-handling problems. The automotive industry has become the main sector using sustainable composite materials. The material properties of the product, combined with its light weight, mechanical and acoustic performance, recyclability, and vibration-damping characteristics, provide benefits that reduce CO_2 emissions and enhance fuel efficiency. Natural fiber composites have established their presence throughout the automotive industry as materials for interior components, including door panels, dashboards, seat backs, roof liners, and insulation panels [9, 24].

Wool is a natural fiber produced by sheep from their hair, composed mainly of α-keratin, which contains carbon, hydrogen, oxygen, nitrogen, and sulfur [25]. Wool possesses a hierarchical structure comprising a cuticle surrounding its cortex, which contains ortho- and para-cortical cells, and a cell membrane complex that determines its capacity to withstand mechanical stress and moisture [26, 27]. The unique properties of wool make it suitable for acoustic and thermal insulation, as well as for industrial, medical, and fertilizer production, because it naturally breaks down [28]. In addition, wool products provide comfort through their elasticity, moisture control, and ability to insulate with air pockets, and their natural shine helps people sleep better, smell better, stay safe from fires, and treat eczema [29]. Further, the use of wool fibers in polymeric composites has grown because these fibers provide superior thermal insulation and sound absorption properties, which are stronger at higher density levels than those of synthetic fibers such as polyester and fiberglass, as well as mineral wool [10]. The combination of physical and chemical surface treatments of wool fiber enhances compatibility with hydrophobic polymer matrices, thereby improving mechanical performance in composite materials [8] as shown in Table 1. As noted in a recent review, combining hydrophilic wool fibers with hydrophobic polymers poses bonding challenges that warrant attention [28, 30]. Notably, various eco-friendly treatments, including enzymatic, plasma, ozone, low-liquor-ratio dyeing, and bio-based dyes, help reduce water consumption, chemical waste, and environmental impact in the production of these fibers .

Silk, like other animal fibers, can be considered a natural composite system with a hierarchical structure that contributes to its unique mechanical behavior [31][30]. Silk is valued for its natural luster, softness, lightweight nature, and thermal regulation, and is perceived by consumers as a premium and environmentally friendly material [25]. Altman et al. revealed that silk is a protein-based fiber mainly composed of fibroin and sericin, consisting primarily of carbon, hydrogen, oxygen, and nitrogen, and they confirmed that silk is a natural, biodegradable, and renewable animal-derived fiber produced by silkworms, offering an environmentally friendly alternative to petroleum-based synthetic fibers [31,32]. In addition, polymer composites reinforced with silk fibers of different sizes, orientations, and contents are classified as biocomposites [24]. Silk fibers possess a hierarchical structure composed of crystalline β-sheet regions embedded in an amorphous matrix, which governs strength, flexibility, and toughness [33]. Noteworthy research has also shown that silk fibers exhibit high tensile strength, remarkable toughness, and high elongation at break, making them one of the strongest natural fibers [34,32]. It was also found that silk fibers are widely used in biomedical fields because they serve as sutures, tissue-engineering scaffolds, and drug-delivery systems, all of which require biocompatible, biodegradable materials [35]. However, the hydrophilic nature of silk leads to weak interfacial interactions with hydrophobic polymer matrices, resulting in reduced mechanical performance of composite materials despite their excellent material properties [36]. Silk shows high toughness and elongation, while wool demonstrates intrinsic fire resistance. Their biocompatibility enables applications in biomedical and tissue engineering fields, and they may be biodegradable, depending on the polymer matrix [44]. Further, animal fibers generally have higher costs and more variable quality compared to plant fibers. Processing limitations include sensitivity to alkalis, enzymes, and heat, as well as potential odor and contamination issues. The large-scale adoption of technology in the supply chain is hindered by ethical issues and supply chain constraints [45].

Basalt fiber is an environmentally friendly material because it originates from volcanic rock and aligns with sustainable composite manufacturing methods that use natural waste materials derived from mineral resources [37,34]. The production of basalt fibers is almost pollution-free and consumes less energy compared to synthetic fibers. Basalt fibers require no chemical additives during production and generate no hazardous by-products [38]. They also have a lower carbon footprint than glass or carbon fibers, contributing to sustainable engineering structures. Basalt fibers exhibit high mechanical strength, excellent temperature resistance, good chemical stability, and durability in aggressive environments. They offer high performance and durability under harsh operating conditions due to their resistance to acids, alkalis, and high temperatures (up to 800 °C) [39]. The performance of basalt fiber composites strongly depends on fiber–matrix adhesion, which is often improved by surface treatments and sizing agents. Liu et al. demonstrated that basalt fiber-reinforced polymers (BFRPs) have good corrosion resistance, design flexibility, and suitability for electrical and structural

applications. In addition, BFRPs meet the requirements of electrical equipment, such as insulating rods, composite cross-arms, and new conductors, due to their mechanical and insulating properties. Zhou et al. demonstrated that BFRPs are used in the construction, automotive, marine, and aerospace sectors due to their lightweight nature, corrosion resistance, and thermal stability. Basalt fibers offer multiple benefits yet face obstacles that hinder their effective use in real-world applications. The production process is constrained by technical limitations and the need to maintain product quality [37, 34,38]. Differences in raw basalt material lead to variations in fiber properties, making standard product development difficult [39]. The current obstacles demonstrate the urgent need for improved production methods and quality control standards, which will enable the complete utilization of basalt fiber composite materials' mechanical strength and environmental benefits. It has been shown that basalt fibers have tensile strength and elastic modulus that match those of synthetic E-glass fibers. They also offer excellent resistance to high temperatures and chemical degradation, making them suitable for construction and fire-resistant applications. Life cycle assessments indicate a lower environmental footprint than some synthetic fibers [37,40]. Don et al. demonstrated that basalt fibers tend to fail in a brittle manner, necessitating careful composite design and effective toughening strategies. In addition, fiber-matrix adhesion can be limited in the absence of surface treatments or sizing agents. Additionally, industrial standardization and supply-chain maturity are still developing in some regions. Therefore, each type of reinforcing material possesses unique properties that make it suitable for specific applications. Compared to plant fibers, wool offers superior thermal and acoustic insulation, while silk provides higher durability and biocompatibility, making it suitable for medical and biological applications. Basalt fibers, on the other hand, excel in thermal stability, mechanical strength, and chemical corrosion resistance, making them a suitable choice for construction applications and high-temperature environments. Thus, selecting the appropriate reinforcing material depends on balancing mechanical, thermal, environmental, and economic performance requirements according to the nature of the intended application [41].

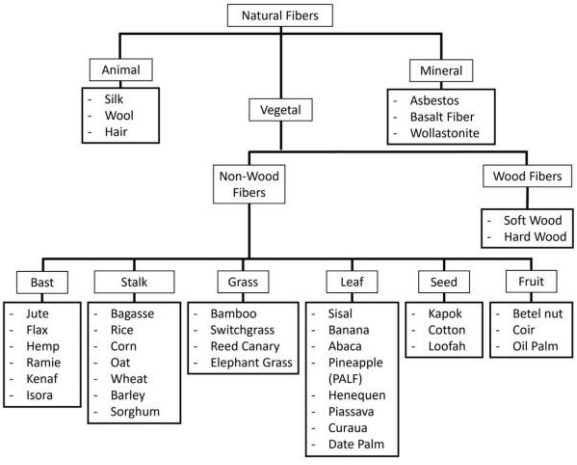


Figure 2. Schematic illustration of Eco-friendly natural fibers in polymer composites for sustainability. [75]

Table 1. Mechanical properties of different natural fibers compared to conventional fibers [79]

Fiber	Density (g/ cm^{-3})	Tensile strength (MPa)	Youngs Modulus (GPa)	Elongation at break (%)	Equilibrium moisture content (%)
Cotton	1.6	287-597	5.5-12.6	7-8	-
Jute	1.44	393-773	10-30	1.5-1.8	12
Flax	1.54	345-2000	27-85	1-4	7
Hemp	1.47	368-800	17-70	1.6	9
Kenaf	1.2	240-930	14-53	1.6	-
Ramie	1.56	400-1000	27-128	1-4	9
Coir	1.25	220	6	15-25	10
Sugar plam	1.5	421.4	10.4	9.8	-
Sisal	1.33	600-700	38	2-3	1
Pineapple	1.5	170-1627	82	1-3	13
Banana	1.35	335	33.8	5.3	-
Bamboo	0.6-1.1	140-230	11-17	-	8.9
E-glass	2.5	2000-3500	70-77	4.5-4.9	-
S-glass	2.5	4570	86-90	4.5-4.9	-
Aramid	1.45	3400-4000	130-185	2.5	-
Carbon	1.9	3400-5400	230-440	1.8	-

4.Evolution of Eco-Friendly Particles Reinforced Polymer Composites (EFPRPCs)

Particle-reinforced composites use micro- and nanoscale discrete particles distributed within a matrix material. The most commonly used reinforcement materials are ceramics, ash, agro-waste powders, and industrial by-products [47]. The performance of the system depends on three factors: particle size distribution, particle shape, and particle bonding strength. Previous research has indicated that particles enhance the mechanical and thermal properties of polymer composite materials. However, the continuous load-transfer paths necessary for strength development in composites are absent in particle-reinforced composites, resulting in lower tensile strength compared to fiber-reinforced composites [48]. Although particle-reinforced composites exhibit lower tensile performance, they improve surface properties while reducing material costs [49]. Achieving uniform particle distribution in composites is challenging because waste particles cluster and segregate, leading to performance degradation. Moreover, weak interfacial bonding between waste particles and the matrix can limit effective load transfer and mechanical efficiency [49]. To address this issue, manufacturing processes such as stir casting require careful optimization of parameters, including stirring speed, temperature, and volume fraction, to minimize porosity and particle loss [50].

A major trend that emerged in the last decade is the shift toward eco-friendly, waste-derived particulate fillers, which can partially or fully replace traditional inorganic fillers and are eco-friendly particle reinforcements (EFPRCs) [37,34]. Eco-friendly particulate reinforcements (EFPRCs) can be broadly classified into three main categories, each exhibiting distinct mechanical, environmental, and processing characteristics. [8]. These categories are natural mineral-based particulates,

industrial waste-based particulates, and agricultural waste-based particulates [51,49]. Various eco-friendly particulate reinforcements used in polymer composites are presented in Figure 2. Numerous studies report improvements in stiffness, hardness, and dimensional stability, along with reduced composite density and cost when natural particulates are incorporated.

Natural mineral-based particulates such as basalt powder, diatomite, pumice powder, clay nanoparticles, and talc are widely used as sustainable reinforcements [9]. They are naturally abundant, require minimal processing, and have a lower environmental impact compared to synthetic ceramic particles. These particles improve thermal stability, stiffness, and barrier properties, particularly in lightweight and packaging composites [11,52]. Historically, the development of polymer composites depended heavily on inorganic fillers such as silica (SiO_2), talc, and calcium carbonate ($CaCO_3$). These fillers were widely adopted due to their cost-effectiveness, availability, and ability to improve multiple mechanical, thermal, and dimensional characteristics of polymer matrices. When silica is added to materials at micron- or nanoparticle sizes, it provides substantial reinforcement, resulting in greater material stiffness, improved abrasion resistance, and higher thermal stability of the polymer composite. The handling and processing of certain mineral fillers, especially fine silica, pose health hazards, underscoring the need for safer and more sustainable filler materials. Talc particles provide dimensional stability and rigid-body strength, and prevent permanent shape change, making them useful for packaging, automotive parts, and household polymer products. The low cost and ease of dispersion of calcium carbonate make it one of the most popular filler materials, as it can increase material stiffness while maintaining moderate toughness across various loading levels [53,52]. The extraction and processing of inorganic minerals cause environmental problems, including land degradation, high energy requirements, and the production of fine particulate waste [34, 37].

Industrial waste-based particles repurpose heavy industry byproducts that would otherwise cause environmental pollution [54]. Common examples include fly ash, red mud, waste glass powder, and slag particles [40]. These reinforcements eliminate hazardous waste streams, reduce the need for energy-intensive ceramic fillers, and improve fatigue and mechanical performance [48]. Moreover, they offer high thermal resistance and low cost, making them suitable for construction materials and metal matrix composites [50]. Biochar is a bio-based particulate material produced through the pyrolysis of biomass waste. It is considered a carbon-negative reinforcement material. These particles reduce carbon footprint through renewable sources and low-energy production routes [54,53]. It is lightweight and enhances wear resistance, stiffness, and thermal conductivity in polymer composites such as HDPE, epoxy, and PLA [54,55]. Its applications include automotive interior components, sustainable packaging, and low-carbon building materials [11].

Agricultural waste-based particulates are biodegradable or bio-waste-derived materials added to polymer or metal matrices to enhance mechanical, thermal, or tribological properties while reducing environmental impact [54]. They support sustainability by lowering carbon footprint, valorizing waste, and replacing energy-intensive synthetic fillers such as SiC or Al_2O_3 [11]. Furthermore, these dispersed eco-friendly particles enhance hardness, wear resistance, dimensional stability, and cost-effectiveness [56]. Agricultural waste particles are among the most important eco-friendly reinforcements because they convert abundant biomass waste into high-value composite materials [49]. Agricultural residues such as rice husk ash, coconut shell powder, olive stone powder, and nutshell particulates have gained attention for their abundance, biodegradability, and reinforcement potential [52, 56, 57]. These materials are produced globally in large quantities, making them low-cost and renewable, while reducing landfill disposal and open-burning pollution [48]. Many of these waste materials naturally contain silica, calcium, lignocellulosic structures, or carbon-rich phases that enhance polymer performance [53]. Their silica, carbon, and lignocellulosic content enhances the stiffness and hardness of polymer composites [40, 49]. Prior research has shown that rice husk ash contains 85-95% amorphous silica, making it an effective, sustainable alternative to synthetic silica fillers [34, 37]. Researchers have used eggshell powder, which contains high levels of calcium carbonate, as a substitute for mined calcium carbonate because it retains most of its mechanical properties. The study showed that surface-modified fruit and nut shell particles can enhance both stiffness and hardness in hydrophobic polymer matrices. Valorization of agricultural waste reduces disposal costs, supports circular economy principles, and creates value-added composite materials.

Most waste-based fillers require minimal processing, such as washing, drying, grinding, or mild thermal treatment, making them more sustainable than mineral mining and milling [53,57]. Notably, with appropriate surface treatments, such as silane coupling agents or alkaline treatment, natural waste fillers can achieve reinforcement levels comparable to conventional inorganic fillers. So, people choose to use natural waste-derived fillers instead of synthetic materials to protect the environment and to help their businesses [34, 37].

In the context of nanoparticles, bio-derived nanoparticles include nanocellulose, chitin, chitosan, starch, and lignin nanoparticles, which are fully renewable, biodegradable, non-toxic, and exhibit extremely high specific strength at the nanoscale [11, 58, 59]. These nanofillers possess extremely high surface area-to-volume ratios, enabling efficient stress transfer and significant enhancement of mechanical, thermal, and barrier properties at low loadings [8]. Presently, numerous studies indicate that these nanoparticles significantly improve the mechanical, thermal, and barrier properties of sustainable polymer composites [60]. Furthermore, their typical applications include sustainable packaging, biomedical biocomposites, and lightweight structural polymers [58]. According to research by Faruk et al., the tensile strength, Young's modulus, and fracture toughness of nanocellulose-based polymer composites show substantial improvements in practical applications [11]. The use of advanced dispersion methods, which include ultrasonic mixing and surface modification techniques, is necessary to address the critical issue of nanoparticle agglomeration [60]. The research by Alshammari et al. indicates that using natural waste particles as substitutes for inorganic fillers poses multiple technical challenges [57]. On the other hand, D. N. Syuhada and A. R. Azura showed that the use of natural

fillers results in a non-uniform particle-size distribution, moisture absorption, and lower thermal stability than mineral fillers [53]. Also, the hydrophilic surfaces of these materials form weak interfacial bonds with hydrophobic polymers, leading to a loss of strength, except when the surface is modified [8, 37]. Therefore, the surface treatment of used nanoparticles is essential to prevent a reduction in tensile strength, impact resistance, and moisture durability. In conclusion, a comparison between particles derived from agricultural and industrial waste indicates that the final performance of composites depends largely on particle size, distribution, and the nature of their interfacial bonding with the polymer matrix. While many of these particles offer clear environmental and economic benefits, the resulting mechanical improvements are often less than those achieved with continuous fibers, thereby limiting their use in construction applications requiring high strength [11].

The shift towards using particles derived from natural waste instead of traditional inorganic fillers has led to increased interest in assessing the environmental impact of these materials. Therefore, life cycle assessment (LCA) is one of the most important tools for evaluating the environmental performance of eco-friendly polymer composites. It enables the study of the product's environmental impacts throughout its life cycle as shown in the figure 3, from raw material extraction and manufacturing to transportation, use, and final recycling or disposal. LCA studies rely on a range of important environmental indicators such as carbon footprint, energy consumption, potential for global warming, and recyclability. Recent studies have shown that composites reinforced with natural fibers have a lower carbon footprint and energy consumption than those reinforced with synthetic fibers, such as glass and carbon fibers. Furthermore, the use of natural fibers helps reduce greenhouse gas emissions and improve the efficiency of natural resource use. The recyclability and biodegradability of these materials also make them more compatible with the principles of the circular economy and environmental sustainability. Thus, life cycle assessment has become an essential tool for determining the environmental feasibility of composite materials and guiding the development of more sustainable composite systems with a low environmental impact [74].



Figure 3. Sustainability of NFRPCs [78]

5.Hybrid and Modified EFRCs (Eco-Friendly Reinforced Composites)

Eco-friendly reinforced composites use hybridization to combine multiple reinforcement types in a single composite and improve the mechanical strength and durability of single-fiber composites [61]. Researchers indicated that hybridization enhances load transfer, tensile strength, and impact resistance while preserving the environmental advantages of natural fibers [62]. A comprehensive review clarified the effect of combining natural plant-based fibers with synthetic reinforcements such as glass, basalt, or carbon fibers in hybrid composites and showed that hybridization improves mechanical performance by increasing tensile and flexural strength while reducing reliance on synthetic materials [63]. Hybridization of jute fibers with agave or vetiver fibers, together with optimized stacking sequences, improves strength and wear resistance. In addition, coconut shell powder and banana fibers improve the machining and drilling performance of hybrid polymer composites [6]. Saleem et al. showed that new processing methods, including fiber surface treatments and matrix modification techniques, advance hybrid composite materials by enhancing material performance and durability. These hybrid materials should be used in automotive interior panels, building insulation materials, and consumer products because they provide better mechanical performance and reduced environmental impact [46]. Combining plant- or animal-derived natural fibers with basalt or glass fibers via hybrid composite technology creates materials that surpass the individual strengths of their components by combining natural-fiber sustainability with vibration absorption [46]. Ajayi et al. [64] showed that sisal/glass-fiber and flax/basalt-fiber hybrid polymer composites performed better under load than single-fiber systems. The previous investigation showed that natural–nano hybrid composites, which combine plant fibers with nanoclay, provide improved mechanical and thermal performance while exhibiting multiple functions, including enhanced barrier protection and fire resistance.

6.Modifications of Eco-Friendly Reinforcements in Polymer Composites

Bio-composites need durability improvements in moisture resistance, flame retardancy, and antibacterial resistance to increase their operational lifespan, but it is essential to achieve these improvements without using harmful substances or disrupting recycling processes. The principle of sustainable composite design has shifted toward developing low-impact modification strategies that maintain material strength, sustain performance over time, and reduce environmental damage, as noted by Suriani et al. [63]. Modification in EFRCs involves applying chemical or physical treatments to fibers or filler particles to improve fiber-matrix or particle-matrix adhesion. Natural fibers are hydrophilic, whereas most polymer matrices are hydrophobic, which can prevent proper interfacial bonding unless treated [65, 66]. Achieving an optimal balance between mechanical strength, long-term durability, and environmental sustainability is a central challenge in the development of eco-friendly natural fiber-reinforced composites. While surface treatments and functional modifications can significantly enhance

interfacial bonding and mechanical performance, excessive chemical processing may compromise biodegradability and increase environmental burden [64]. It was reported that alkali (NaOH) treatment to remove hemicellulose/lignin and improve adhesion, thereby exposing more reactive hydroxyl groups and enhancing mechanical interlocking with the matrix. While the silane coupling agents are used for better fiber/matrix compatibility [66] [65]. Collectively, these chemical modifications have been shown to enhance the EFRPCs properties. However, aggressive chemical treatments may damage the integrity of natural fibers and reduce intrinsic strength; treatment byproducts and processing solvents raise environmental and cost concerns [8]. Beyond interfacial chemical treatments, functional surface modifications are increasingly applied to natural fibers and particulate reinforcements to impart additional performance attributes such as flame retardancy and antimicrobial activity, thereby extending their applicability in high-value engineering, biomedical, and packaging applications [68].

The researchers demonstrated that surface coatings combined with bio-based resin systems yield better EFRPC performance than previous analytical methods used to test these materials. It was stated that nanocoatings reduce moisture absorption, whereas functional coatings, which contain flame-retardant bio-phosphorus compounds and antibacterial agents such as chitosan and silver nanoparticles, provide additional benefits to composite materials while maintaining their eco-friendly properties. The process of creating functional surface modifications offers practical benefits but also presents multiple technical challenges and environmental sustainability issues. The application of flame-retardant coatings to composite materials increases density and stiffness, but the bonding strength depends on the effectiveness of the integration process, while antibacterial nanoparticle systems attract regulatory attention due to health and environmental safety concerns [11]. The advanced natural fiber composite systems will achieve their future applications with success when their functional performance achieves compatibility with both mechanical reliability and life-cycle sustainability [28, 66]

7.Processing and Fabrication Techniques of Eco-Friendly Reinforcement Polymer Composites

7.1 Conventional Processing Methods

The Hand Lay-Up method, due to simplicity, low cost, and suitability for fibers such as flax, jute, and hemp, is widely utilized for natural fiber composites [69]. Furthermore, to enhance fiber wetting and reduce void content, mechanical properties can be improved by compression molding [11]. Also, injection molding is suitable for short natural fibers combined with thermoplastic matrices and allows high-volume automated production. However, fiber length must be limited to prevent degradation and ensure proper melt flow [8]. On the other hand, extrusion is a continuous melt-processing technique commonly used for biocomposites with uniformly dispersed natural fibers. However, processing temperature and screw design strongly influence fiber dispersion and final mechanical performance [70]. Vacuum Infusion / Resin Transfer Molding (RTM) is another process suitable for woven natural fibers, enabling good resin penetration and low void formation. These methods provide improved fiber or particle volume fraction and better surface quality than open-mold techniques as shown in table 2. It was indicated that spray layup is limited to use with natural fibers and can be adapted to short natural fibers, although control over fiber length and orientation is limited. It is mainly used for non-structural natural-fiber composite products [8]. The vacuum bagging process is a traditional enhancement of hand lay-up that improves resin distribution and reduces porosity. It is suitable for woven or stitched natural fiber fabrics [71]

7.2 Advanced and Emerging Techniques

Advanced and emerging techniques in biopolymer composites are important because they enable meticulous control of structure, interfacial bonding, and processing, resulting in significant improvements in mechanical, thermal, and environmental performance. Moreover, these methods are instrumental in creating eco-friendly, lightweight yet strong biocomposites, which broaden their use in high-tech engineering, medical, and green industry applications. Vacuum infusion and vacuum-assisted resin transfer molding (VARTM) are widely used closed-mould techniques for EFRPCs reinforced with fibers such as woven fabrics, unidirectional fibers, and mats, and are used with epoxy, vinyl ester, and polyester resins. The process relies on vacuum pressure to draw resin through dry fiber preforms, ensuring uniform impregnation, reduced void content, and improved fiber/matrix bonding under controlled curing conditions. [71]. Hot pressing and thermoforming are established high-throughput consolidation methods for thermoplastic composites, producing semi-structural laminates with good dimensional accuracy. Thermoforming shapes preheated laminates above Tg or Tm, while hot pressing applies heat and pressure to consolidate plies, reduce porosity, and enhance interlaminar bonding [1]. Moreover, 3D printing, i.e., additive manufacturing (AM), fabricates EFRPC parts layer-by-layer from CAD data, enabling complex geometries and customized designs using fiber-filled or continuous-fiber-reinforced feedstocks. Mechanical performance is strongly influenced by 3D processing parameters such as layer orientation, interlayer bonding, and fiber alignment, which govern anisotropy and void formation [72]. Additionally, resin film infusion (RFI) is a closed-mould process in which a predetermined resin film melts and infuses natural fiber preforms under heat and vacuum. The method shows enhanced fiber wet-out, reduced resin waste, and improved thickness control compared to conventional infusion [73]. Also, Pultrusion is a continuous process for producing constant cross-section profiles using natural fibers such as flax, jute, and hemp impregnated with thermoset resins. It provides good fiber alignment and consistent quality and is increasingly being explored for use in sustainable structural components [20]. Filament winding can also be adapted for hybrid EFRPCs, in which natural fibers are combined with synthetic fibers to improve strength and sustainability. The method offers precise fiber placement and high fiber volume fractions**.** Finally, bio-based sheet molding compound incorporates short natural fiber within a thermoset matrix for compression molding of complex shapes. It enables fast cycle times and is suitable for automotive interior and semi-structural components [8].

Table 2. Common manufacturing processes for polymer composites [76][77]

Manufacturing process	Advantage	Limitations	Applications
Hand Lay-up	Low equipment cost, suitable for prototypes and complex shapes, easy to implement	It depends on the worker's skill, the likelihood of gaps, and low productivity.	Marine structure ، Automotive prototype ،Wind turbine blades
Compression molding	High production speed, good dimensional accuracy, high mechanical properties, suitable for mass production	The cost of molds is high, making it uneconomical for small-scale production.	Automotive components ، Electrical parts
Resin Transfer Molding (RTM)	Good fiber impregnation, excellent surface finish, low voids, high quality	Higher equipment and mold costs; requires precise process control.	Aerospace ، Automotive ، Structural components
Vacuum Infusion	Reduced gaps, improved fiber ratio, lower resin consumption, suitable for large pieces	Longer manufacturing time, requires expertise in vacuum control.	Marine structures ،Wind turbine blades ، Large composite panels
Pultrusion	Continuous production, consistent quality, high productivity, low cost of mass production	It is limited to sections with a fixed section.	Structural profiles ، Bridges ،Utility poles
Filament Winding	High fiber content, excellent resistance, suitable for cylindrical parts	It is limited to axial shapes	Pressure vessels ،Pipes ، Storage tanks
Injection molding	High production speed, suitable for complex shapes, high automation capability	Often used with thermoplastics and short fibers, it has lower properties than continuous fibers.	Consumer products ، Automotive interiors
Additive Manufacturing	reduced material waste, suitable for custom parts	Low production speed, challenges in achieving high mechanical properties	Biomedical devices ، Aerospace prototypes ، Customized composite parts

8.Conclusions and future recommendation

- This study reviewed environmentally friendly reinforcing materials, including natural fibers derived from plants and animals, hybrid systems, and particle reinforcing materials. It demonstrated their effects when combined with fibers, linking their performance to environmental sustainability, life cycle assessment, and the circular economy. The study also discussed key manufacturing methods, a topic largely overlooked by previous research.
- Plant fibers such as flax, hemp, jute, and kenaf exhibited good mechanical properties relative to their low weight, making them suitable for transportation and lightweight construction applications. Wool and silk offer advantages in thermal and acoustic insulation and biocompatibility, while basalt fibers are characterized by high mechanical strength and excellent thermal and chemical stability, making them suitable for structural applications and harsh environments
- The review also showed that surface modification, such as alkaline and silane treatments, plays an important role in improving the interfacial bond between the fiber and matrix, reducing moisture absorption, and enhancing the composite's mechanical properties.
- From an environmental perspective, life cycle assessment (LCA) studies have shown that many eco-friendly reinforcing materials have a lower carbon footprint, require less energy, and are more recyclable compared to traditional synthetic reinforcing materials. Furthermore, using agricultural and industrial waste as reinforcing materials contributes to waste reduction and promotes the principles of a circular economy.

8.1 recommendations

- Future studies should focus on developing standardized methods for testing natural reinforcing materials to minimize variations in properties caused by biological and environmental factors.
- Existing surface treatment techniques, such as alkaline treatment, silane treatment, and nano-coatings, need to be improved to enhance the bond between reinforcing materials and the polymer matrix, reduce moisture absorption, and maintain environmental sustainability.
- The use of bio-resins should be expanded to enable the development of fully sustainable polymer composites. Further research on advanced manufacturing techniques, such as vacuum injection molding and additive manufacturing, is recommended to improve industrial production, quality control, and product reproducibility.
- Life cycle assessment (LCA) studies should be expanded to accurately assess the environmental benefits of eco-friendly polymer composites.
- It is essential to evaluate the long-term performance of eco-friendly composites under various operating conditions, including humidity, UV exposure, thermal cycling, and repeated mechanical stresses. Strengthening collaboration between academia and industry is recommended to accelerate the transfer of research findings to scientific applications and to develop standardized design criteria and effective recycling strategies that support the principles of the circular economy and sustainability.

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