Environmentally Friendly Composites from Agricultural Residue Biomass for Lightweight Applications in New Generation Structures: A Review

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The increasing global demand for sustainable materials has spurred extensive research into biopolymer-based composites derived from agricultural residue biomass. These materials offer an eco-friendly alternative to petroleum-based composites, addressing environmental pollution, resource depletion, and the need for low-density materials in sectors such as automotive, aerospace, packaging, and construction. This research focused on low-density bio-based composites as sustainable options for lightweight applications in automotive, aerospace, packaging, and construction. It highlights the use of agricultural residue and discontinuous binder systems to reduce density, as well as manufacturing techniques that improve structural efficiency. It emphasizes critical composite properties such as mechanical strength, thermal behavior, water resistance, biodegradability, and lightweight characteristics. The influence of fiber content and processing parameters on overall performance is also discussed. In addition, the review highlights major challenges, including scalability, cost-effectiveness, and long-term stability and proposes future research directions focused on durability enhancement, production efficiency, and commercial viability. Overall, this work underscores the transformative potential of agricultural residue-derived bio composites in advancing sustainable, high-performance materials for lightweight and eco-conscious construction and industrial applications.

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INTRODUCTION

The development of lightweight composites using agricultural residue biomass offers a compelling solution to the dual challenges of sustainable material innovation and agricultural waste valorization. As global industries shift toward eco-conscious practices, there is increasing demand for materials that are not only renewable and biodegradable but also optimized for low-density structural applications (Singh *et al.* 2022; Maraveas

2020; Stalin and Shobhanadevi 2021). Agricultural residues serve as a feasible substitute for traditional fillers and reinforcements, offering the additional benefit of decreasing the overall weight of composite structures. This reduction is a crucial factor in the automotive, aerospace, packaging, and construction industries (Mohanty *et al.* 2022; Ramesh *et al.* 2021).

A fundamental principle in the design of low-density composites is the deliberate preservation of internal porosity or air-filled regions by avoiding complete saturation of void spaces with matrix polymer. Traditional composite approaches often emphasize achieving void-free structures to maximize mechanical integrity; however, this invariably leads to higher density materials. For applications where weight reduction is paramount, such as in lightweight panels or energy-efficient structural elements, a different strategy is required—one that carefully balances mechanical performance with the inclusion of voids or the use of minimal and discontinuous binder phases.

Agricultural residue biomass, being abundant, cost-effective, and rich in the structural polymers cellulose, hemicellulose, and lignin, provides an excellent basis for such lightweight systems. These materials exhibit favorable properties including biodegradability, low density, and acceptable tensile characteristics, making them attractive candidates for structural and semi-structural applications where weight reduction is essential (Rani *et al.* 2023; Palanisamy *et al.* 2024). Natural fibers derived from residues can significantly enhance the mechanical profile of a composite without necessitating full matrix impregnation, allowing for the design of partially bonded or binder-reduced systems that retain sufficient integrity for specific use-cases (Lizundia *et al.* 2022).

Beyond mechanical properties, agricultural residues such as tamarind shell powder and coconut shell fiber contribute desirable thermal and abrasion resistance, making them well-suited to lightweight composites intended for demanding environments (Phiri *et al.* 2023b; Ayrilmis *et al.* 2024). Their integration also aligns with the principles of circular economy by transforming agricultural waste into value-added products, thereby reducing residue accumulation while supporting rural and regional economies (Palanisamy *et al.* 2023; Kumar *et al.* 2024).

Despite these advantages, challenges remain in ensuring performance consistency, as natural fibers are affected by variables such as growth conditions and processing methods (Arzumanova 2021). Surface treatments and fiber modification techniques are increasingly applied to enhance fiber–matrix interaction, particularly in systems where the binder is reduced or intentionally discontinuous. Likewise, advances in fabrication methods such as compression molding and thermomechanical pressing enable the creation of structurally efficient, low-density panels with tailored porosity and minimal synthetic input (Russo *et al.* 2021; Manickaraj *et al.* 2024a).

The use of agricultural biomass in such composites significantly lowers the environmental impact when replacing synthetic materials (Olofsson and Börjesson 2018). Importantly, the sustainability of the final product depends not only on the biodegradability of the fiber but also on the matrix used. Researchers must be cautious in distinguishing between fully biodegradable systems (*e.g.*, natural fiber + biopolymer) and partially biodegradable or non-biodegradable composites (*e.g.*, natural fiber + synthetic resin) (Petersen 2008; Singh *et al.* 2021).

This review examines the function of agricultural residues in the production of lightweight composite materials, emphasising methods that deliberately decrease composite density. This is achieved not only through the selection of low-density fillers but also by reducing matrix content and utilising internal porosity. This document outlines recent advancements in material selection, binder reduction, structural design, and processing techniques that facilitate the development of next-generation lightweight biocomposites (Phiri *et al.* 2023a; Gupta *et al*. 2022b). Various agricultural residues that are commonly accessible, such as rice husks, banana fibres, tamarind shells, and corn stalks, are analysed for their potential use in low-density systems (Palanisamy *et al.* 2022b).

Additionally, the potential of binder-free or minimally bonded structures is addressed, especially in thermal-pressed and biodegradable panel systems in which natural fiber compaction and lignin content contribute to mechanical cohesion (Cardoen *et al.* 2015). These approaches represent a significant step toward reducing chemical inputs and achieving lightweight, environmentally responsible materials for the future.

This review explores environmentally friendly composites from agricultural residues, structured around key sections that highlight material performance, sustainability, and lightweight design. It begins with biopolymers in sustainable composites, followed by an overview of agricultural residues as reinforcements or fillers. A central focus on factors affecting composite density examines how reduced matrix content and controlled porosity contribute to lightweight structures. Fabrication techniques and surface treatments are discussed for optimizing properties and consistency. The review also covers applications in construction, automotive, and packaging, and concludes with end-of-life strategies aligned with circular economy goals (Sommer *et al.* 2015; Biswas *et al.* 2022; Satankar *et al.* 2024).

BIOPOLYMERS IN SUSTAINABLE COMPOSITES: TYPES AND STRUCTURES

Biopolymers are fundamental to the advancement of sustainable composites due to their biodegradability, renewability, and ability to effectively bind natural fiber reinforcements into eco-friendly, lightweight, and high-performance materials (Das *et al.* 2023; Khalil *et al.* 2023; Deshmukh *et al.* 2024). Derived from biological sources, biopolymers offer an environmentally benign alternative to petroleum-based plastics, making them integral to the development of sustainable materials in packaging, biomedical, agricultural, and automotive sectors (Nagalakshmaiah *et al.* 2019; Monia 2024). This section presents an integrated overview of the key biopolymers used in sustainable composites, focusing on their chemical structures, properties, and applications. Figures 1 and 2 show the types of bio polymers.

Polylactic Acid (PLA)

Polylactic acid (PLA) is a thermoplastic aliphatic polyester synthesized primarily from renewable resources such as corn starch, sugarcane, or cassava. The production of PLA can begin with the fermentation of carbohydrates extracted from these crops to produce lactic acid, which is subsequently polymerized either by direct condensation or by ring-opening polymerization of lactide, the cyclic dimer of lactic acid (Udayakumar *et al.* 2021).

Chemically, PLA is a linear polyester with the repeating unit $(C_3H_4O_2)_n$ consisting of ester linkages (-COO-) between lactic acid monomers. PLA exists in stereochemical forms such as poly-L-lactic acid (PLLA), poly-D-lactic acid (PDLA), and their racemic mixtures (PDLLA), which influence its crystallinity and mechanical behavior (Sharahi *et al.* 2024).

PLA can break down into water and carbon dioxide under industrial composting conditions, which require high heat and moisture, helping to reduce its environmental impact in those controlled settings. Its mechanical strength and rigidity are comparable to traditional plastics such as polyethylene terephthalate (PET), although its relatively low glass transition temperature (50 to 60 °C) limits its use in high-temperature applications. Innovations in blending and additives are helping to overcome this limitation (Yaashikaa *et al.* 2022). PLA is widely used in packaging (*e.g.*, cups, plates, and films), biomedical applications (including sutures, drug delivery systems, and orthopedic implants), and 3D printing, where its processability and renewability make it a preferred material (Biswal 2021).

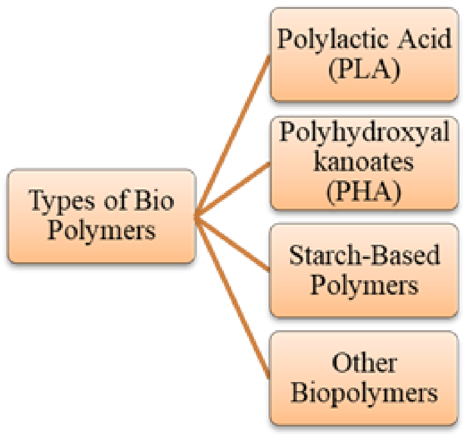

Fig. 1. Types of biopolymers

Fig. 2. Types of bio polymer pellets: (a) PLA, (b) PHA, (c) Starch, and (d) PCL

Polyhydroxyalkanoates (PHA)

Polyhydroxyalkanoates (PHAs) are a diverse family of biodegradable polyesters naturally produced by microorganisms under nutrient-limited conditions as intracellular carbon and energy storage. These biopolymers are synthesized from various carbon sources, including sugars, lipids, and residue materials, aligning their production with circular bioeconomy principles (Fertahi *et. al* 2021; Nanda *et al.* 2022).

PHAs share a general chemical structure $(-O-CHR-CO-)_n$, in which the side chain RRR varies according to the specific monomer, impacting the polymer's mechanical and thermal properties. The most common PHA, poly(3-hydroxybutyrate) (PHB), is characterized by repeating units $(C_4H_6O_2)n$ containing hydroxyl (-OH) and carbonyl (-CO) groups (Patti and Acierno 2022).

PHAs exhibit superior thermal stability, mechanical strength, and biodegradability compared to many other biopolymers, decomposing safely in soil, marine, and composting environments (Kartik *et al.* 2021; Zhiltsova *et al,* 2024). Their non-toxic degradation products make them suitable for sensitive applications.

Industrially, PHAs are used in biodegradable packaging (bags, containers, films), agriculture (mulch films, controlled-release fertilizers), and medical devices (tissue engineering scaffolds, wound dressings, sutures) due to their biocompatibility and tunable properties (Abou-alfitooh and El-Hoshoudy 2024).

Starch-based Polymers

Starch-based polymers are classified as biodegradable polymers, originating from naturally abundant crops including corn, wheat, potatoes, and tapioca. Starch is a carbohydrate polymer consisting of amylose and amylopectin. It is extracted from these crops and functions as the base material. Native starch possesses inherent limitations, including brittleness and water sensitivity. Consequently, it is frequently subjected to chemical modification or blended with other polymers to enhance its mechanical strength, flexibility, and water resistance. The modification process allows starch-based polymers to fulfill the specifications of diverse industrial and commercial applications, all while preserving their biodegradability (Bledzki and Gassan 1999; Mohammed *et al.* 2022; McClements 2024).

Starch-based biopolymers are derived from abundant polysaccharides found in crops including corn, wheat, potatoes, and tapioca. Starch is a carbohydrate composed mainly of amylose (linear) and amylopectin (branched) glucose polymers with α-1,4 and α-1,6 glycosidic linkages. Native starch is brittle and highly hydrophilic, which limits its direct use; thus, it is chemically modified or blended with other polymers to improve its mechanical and moisture-resistant properties (Duceac and Coseri 2022; McClements 2024).

The general formula of starch is $(C_6H_{10}O_5)_n$, with modifications enhancing its flexibility and barrier characteristics. Its biodegradability and low cost make starch-based polymers suitable for sustainable packaging, disposable products, and agricultural films (Awasthi *et al.* 2022; Kabir *et al.* 2012).

Applications extend to food packaging (cutlery, shopping bags), agricultural mulch films that decompose naturally, and biomedical hydrogels and scaffolds benefiting from controlled biodegradability (Gowthaman *et al.* 2021).

Overall, starch-based polymers exemplify the potential of renewable resources in creating sustainable, eco-friendly materials. Their versatility, affordability, and biodegradability make them a valuable solution to the growing demand for alternatives to petroleum-based plastics, contributing significantly to reducing environmental pollution and fostering a circular economy (Heidari *et al.* 2023; Faruk *et al.* 2012).

Polycaprolactone (PCL)

Polycaprolactone (PCL) is a synthetic, biodegradable polyester synthesized by ring-opening polymerization of ε-caprolactone monomers. Its chemical formula is $(C_6H_{10}O_2)_n$, and it consists of flexible ester linkages that confer a low melting point (~60 °C) and excellent ductility (Fatehi *et al.* 2021).

PCL's slow degradation rate and biocompatibility make it ideal for biomedical applications requiring prolonged structural integrity, such as tissue engineering scaffolds and drug delivery systems (Babaremu *et al.* 2023). Its flexibility also lends itself well to packaging materials such as stretch films. Moreover, PCL blends well with natural fibers and other biopolymers, creating composites with enhanced mechanical properties for use in construction, automotive parts, and consumer goods (Pramanik *et al.* 2023).

Overall, PCL's unique combination of low processing temperature, flexibility, biocompatibility, and controlled degradability makes it a highly versatile material (Fatehi *et al.* 2021). Its ability to blend seamlessly with natural fibers and other biopolymers further enhances its utility, enabling the development of innovative, eco-friendly materials that address the growing demand for sustainable solutions in various industries.

OTHER BIOPOLYMERS

Various biopolymers contribute significantly to the advancement of sustainable materials, providing distinct properties and applications that serve a diverse array of industries. Cellulose derivatives, chitosan, and soy-based polymers are notable for their versatility and eco-friendliness, making them suitable solutions for the increasing demand for renewable and biodegradable materials. Figure 3 classifies the additional biopolymers as referenced by Gheorghita *et al.* (2021).

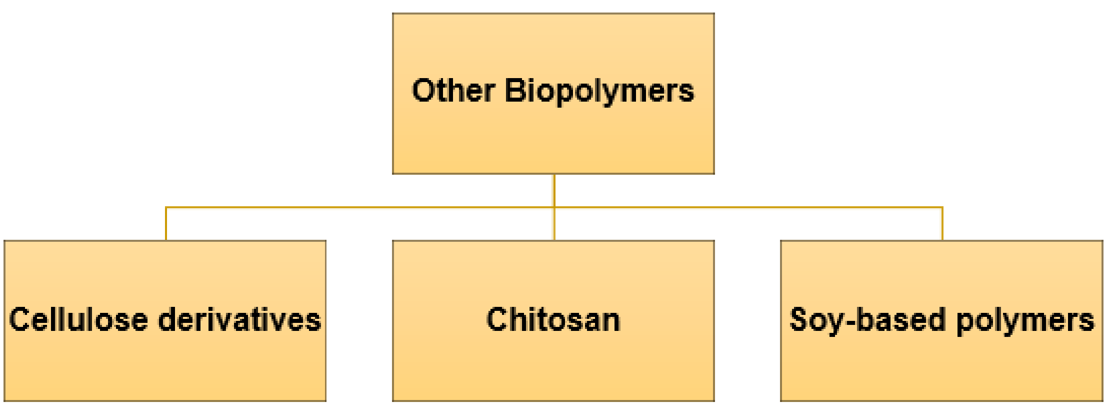

Fig. 3. Other biopolymers

Cellulose Derivatives

Cellulose derivatives are chemically modified forms of cellulose, which is the most abundant biopolymer on Earth. These derivatives are sourced from natural materials, including wood pulp, cotton, and various plant fibers. The derivatives, such as cellulose acetate, carboxymethyl cellulose (CMC), and cellulose nitrate, demonstrate high tensile strength, biodegradability, and superior compatibility with natural fibers, positioning them as optimal choices for reinforcement in biocomposites (Nourbakhsh and Ashori 2010; Garduño-Juárez *et al.* 2024). The modifications improve solubility, mechanical properties, and processing versatility, facilitating a range of applications. In the textile sector, these materials are utilized to produce soft and durable fabrics. In the packaging domain, cellulose-based films and coatings function as biodegradable alternatives to conventional plastics (Noaman *et al.* 2023).

Chemically modified cellulose, such as cellulose acetate, offers enhanced tensile strength and good compatibility with fibers, making it suitable for textiles, coatings, and pharmaceuticals (Garduño-Juárez *et al.* 2024). However, such materials, especially cellulose acetate butyrate (CAB), are resistant to natural degradation due to their dense and hydrophobic nature, which prevents enzyme activity. Therefore, these materials should not be described as degradable unless specifically designed to break down under certain conditions

Chitosan

Chitosan is a polysaccharide obtained from chitin, which is present in the exoskeletons of crustaceans such as shrimp, crabs, and lobsters. The production of chitosan involves the deacetylation of chitin, resulting in a versatile biopolymer. The material exhibits biocompatibility, facilitating safe interactions with biological systems. It is also biodegradable, undergoing natural decomposition in the environment, and it exhibits antimicrobial properties, effectively inhibiting the growth of bacteria and fungi (Westlake *et al.* 2023). The properties of chitosan render it valuable for a range of applications, particularly in water purification, where it functions as a flocculant to eliminate heavy metals and impurities from residue water. The antimicrobial and biocompatible properties render it suitable for biomedical applications, including wound dressings, surgical sutures, and drug delivery systems that facilitate controlled medication release. Furthermore, it serves a dual purpose in agriculture as a natural pesticide and in the cosmetics industry for skin-repairing applications (Gamage *et al.* 2022).

Soy-based polymers

Soy-based polymers, which are derived from soy protein, are renewable and biodegradable materials that have superior adhesion properties. Their sustainability and availability position them as an environmentally responsible option for a range of industrial applications. Soy-based polymers in adhesives offer robust bonding capabilities and are extensively utilized in wood composites and paper products. These materials are utilized in coatings, providing enhanced durability and environmental advantages compared to synthetic alternatives. Additionally, soy-based polymers can function as matrices in biocomposites, integrating with natural fibers to create lightweight, sustainable materials suitable for use in the construction, automotive, and packaging sectors (Li *et al,* 2021). Table 1 summarizes the different biopolymers, including their properties, sources, applications, and environmental impact. Figure 4 shows the combined chemical structure of biopolymers (Christina *et al.* 2024).

Table 1. Comparisons of Different Biopolymers

Biopolymer	Source	Properties	Applications	Environmental Impact
Polylactic Acid (PLA)	Corn, sugarcane, starch	Industrially compostable, transparent, relatively low melting point, good barrier properties to gases	Packaging, disposable cutlery, textiles, medical implants, 3D printing filaments	Can degrade above 60 °C abiotically. Less toxic but energy-intensive production. (Atanase 2021)
Polyhydroxyalkanoates (PHA)	Microorganisms (bacteria)	Biodegradable, thermoplastic, flexible, excellent barrier to water and gases	Biodegradable packaging, medical devices, agricultural films, drug delivery systems	Fully biodegradable, non-toxic, derived from renewable resources. (Gupta *et al.* 2022a)
Starch-based Bioplastics	Starch (corn, potato, rice)	Biodegradable, low cost, can be modified for flexibility, but sensitive to moisture	Food packaging, disposable products, agricultural films	Biodegradable and compostable, low environmental impact but moisture-sensitive and limited strength. (Fredi and Dorigato 2024)
Cellulose-based Plastics	Wood, cotton, agricultural residues	Strong, biodegradable, thermoplastic, and resistant to high temperatures	Films, coatings, biodegradable packaging, and medical uses	Biodegradable, low environmental impact, renewable, but energy-intensive production process. (Liu *et al.* 2021)
Chitosan	Chitin from shellfish or fungi	Biodegradable, antimicrobial, high water solubility, biocompatible	Food packaging, medical applications (wound dressings), water purification	Biodegradable and renewable, but there are concerns over its production from animal sources (shellfish). (Agarwal *et al.* 2023)
Polyhydroxybutyrate (PHB)	Microorganisms (bacteria)	Biodegradable, crystalline, high tensile strength, water-resistant, but brittle	Medical devices, biodegradable plastics, agricultural applications	Biodegradable, but high production costs. Can be synthesized from renewable resources like sugar and vegetable oils. (Losini *et al.* 2021; Pinaeva and Noskov 2024)
Lignin-based Bioplastics	Wood, agricultural residues	Strong, thermal stability, low cost, but brittle and hard to process	Biocomposites for construction, packaging, and automotive parts	Biodegradable, renewable, low carbon footprint, and can reduce residue. However, it requires efficient extraction methods. (Biswas and Pal 2021)

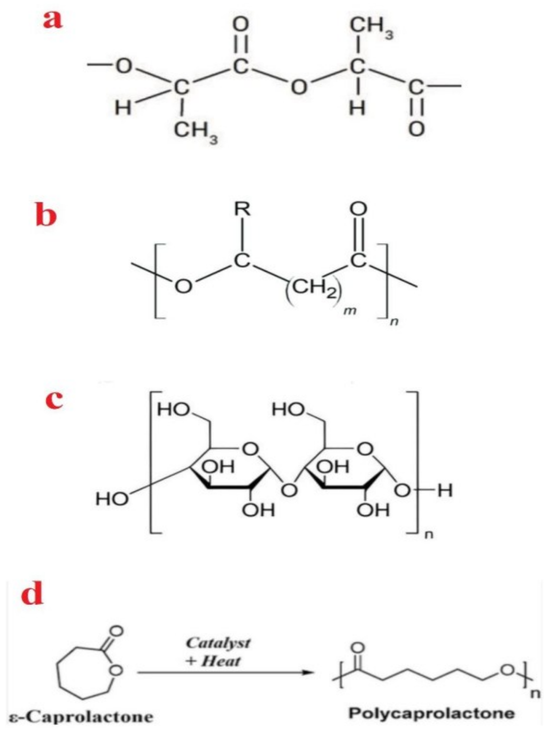

Fig. 4. Chemical structure of biopolymers: (a) PLA, (b) PHA, (c) starch, (d) PCL

AGRICULTURAL RESIDUE

The various categories of agricultural residue biomass are shown in Figs. 5 and 6.

Rice Husk

Rice husks, the protective outer shells removed during the rice milling process, have an annual global production exceeding 120 million tons. Notably, they contain a high silica content (approximately 15 to 20%) and significant cellulose levels, making them attractive as reinforcement materials in polymer composites. The silica contributes positively to thermal stability, flame retardancy, and mechanical rigidity, while the cellulose enhances structural integrity. Studies have shown that rice husk incorporation can improve the tensile strength of polymer matrices such as polypropylene by up to 28% (Saba *et al.* 2022). However, the high silica content can also pose challenges in certain applications, particularly due to its abrasive nature, which may accelerate wear on processing and cutting tools. Untreated husks feature waxy surfaces that hinder fiber-matrix adhesion, weakening composite performance. Surface modifications—such as alkaline (NaOH) and silane treatments are commonly applied to improve compatibility and bonding, and particle size control helps ensure uniform dispersion. Despite processing challenges, rice husks remain promising for use in lightweight construction materials, insulation panels, and eco-friendly packaging (Zarrintaj *et al.* 2023), provided that the abrasive effects of silica are adequately managed.

Fig. 5. (a) Groundnut shell, (b) rice husk, (c) tamarind shell powder, and (d) white straw

Banana Stem Fiber

Fibers derived from the pseudostem of the banana plant exhibit a cellulose content ranging from 60% to 65% and a low lignin content of 7% to 10%. These characteristics contribute to the fibers' notable strength and flexibility (Zarrintaj *et al.* 2023). The fibers demonstrate tensile strengths between 200 and 700 MPa, with a low density of about 1.35 g/cm³. This combination yields an excellent specific strength-to-weight ratio, making them ideal for lightweight composite applications. Reddy and Yang (2005) documented a 35% enhancement in flexural strength and a 41% decrease in density for banana fiber-reinforced epoxy composites at 30 wt% fiber loading, underscoring their applicability in structural components. Nevertheless, the hydrophilic characteristics of banana fibers result in significant moisture absorption, potentially compromising fiber-matrix adhesion and inducing swelling. To address this issue, pretreatments including alkali soaking (NaOH), acetylation, or silanization are frequently utilized to enhance moisture resistance and interfacial bonding. Banana fibers are utilized in automotive components such as dashboards, door panels, and trims, in addition to applications in textiles and biodegradable packaging, due to their essential characteristics of flexibility, lightweight nature, and sustainability (Karuppusamy *et al.* 2023; Ramasubbu *et al.* 2024).

Fig. 6. (a) Coconut fiber, (b) banana fiber, (c) pineapple leaves, and (d) sugarcane bagasse

Coconut Shell Fiber

Coconut shell fiber, derived from the hard outer shell of coconuts, is rich in lignin (~40 to 50%), cellulose (~25%), and hemicellulose, which impart excellent abrasion resistance, hardness, dimensional stability, and impact resistance (Baranwal *et al.* 2022). These properties make it an ideal reinforcement for durable composites used in automotive interiors, furniture, flooring, and construction materials such as composite boards. Baranwal *et al.* (2022) reported that adding 10 to 15 wt% coconut shell powder to epoxy composites increases impact strength by up to 18% and reduces wear by nearly 30%, enhancing mechanical performance. However, the brittleness and rigidity of untreated coconut shell fibers can limit elongation and toughness, often necessitating hybridization with more ductile fibers or surface treatments like alkaline or silane coupling agents to improve dispersion and fiber-matrix bonding. Overall, coconut shell fiber offers a sustainable alternative that reduces dependence on non-renewable materials while delivering high wear resistance and mechanical strength.

Tamarind Shell Powder

Tamarind shell powder, obtained from the grinding of tamarind pod shells, contains a high concentration of lignocellulosic compounds such as polyphenols and tannins. These components provide significant thermal stability and mechanical rigidity (Veeman *et al.* 2021). Incorporating them at a concentration of 5 to 15 wt% into thermoplastic composites can enhance the modulus by as much as 40%, all while maintaining biodegradability. The uniform particle size and hardness render it suitable for applications such as injection-molded components, plastic furnishings, construction materials, and biodegradable packaging solutions. To enhance compatibility with hydrophobic matrices such as polypropylene, it is often essential to employ surface treatments or compatibilizers. Tamarind shell powder contributes positively to the environmental profile and mechanical performance of biocomposites.

Sugarcane Bagasse

Sugarcane bagasse, the fibrous residue left after juice extraction, is rich in cellulose, hemicellulose, and lignin, making it a valuable reinforcement material for biocomposites. Its high cellulose content provides tensile strength and stiffness, while moderate lignin enhances moisture resistance compared to other natural fibers. Studies, such as that of Asyraf *et al.* (2023), have demonstrated that incorporating bagasse fibers into polymer matrices such as PLA improves tensile strength by 17 to 22%, along with increased modulus and water resistance. The low density of bagasse contributes to lightweight composite panels ideal for construction and packaging applications. However, its natural hygroscopicity poses challenges such as swelling and reduced durability, which can be mitigated through chemical treatments including alkaline or silane modifications to enhance fiber-matrix adhesion. Sugarcane bagasse composites are widely used in lightweight building panels, insulation boards, biodegradable packaging, and automotive components, offering a sustainable and eco-friendly alternative to petroleum-based materials while supporting circular economy principles by converting agricultural residue into high-performance products.

Wheat Straw

Wheat straw, an abundant agricultural residue rich in lignocellulosic biomass and containing up to 3% silica, is a valuable resource for producing biodegradable composites (Akhouy *et al.* 2023). Its high cellulose content contributes to the strength and flexibility of composites, while silica influences fiber wettability and mechanical performance. Alkaline-treated wheat straw composites have demonstrated a 22% improvement in compressive strength, making them suitable for building materials. However, untreated straw's surface waxes reduce fiber-matrix adhesion, necessitating pretreatments like alkaline treatment or steam explosion to enhance bonding by removing waxes and increasing surface roughness. Wheat straw composites are widely applied in packaging, building insulation, mulch films, and compostable materials, offering a sustainable and cost-effective alternative to conventional plastics and synthetic materials.

Corn Husks

Corn husks, a byproduct of corn harvesting, are rich in cellulose fibers that offer good flexibility and moderate strength, making them lightweight yet strong reinforcements for biopolymer composites (Ogah *et al.* 2022). These fibers enhance the tensile strength and durability of composites, especially in packaging materials, consumer goods, and insulation products. However, mechanical performance can decline at filler contents above 15 wt% due to fiber agglomeration and void formation. Challenges such as moisture sensitivity and ensuring uniform dispersion are addressed by using coupling agents and thorough drying before processing. Corn husks are widely utilized in biodegradable packaging, disposable cutlery, and flexible insulation products, providing renewable and eco-friendly alternatives to conventional plastics.

Pineapple Leaves

Pineapple leaf fibers (PALF) are strong and durable natural fibers with tensile strength ranging from 400 to 600 MPa and a high Young's modulus, making them ideal for reinforcing biocomposites (Bellili *et al.* 2022). PALF-reinforced epoxy composites exhibit impact strengths comparable to synthetic aramid fibers, proving their suitability for demanding structural applications. These fibers contribute to sustainable composites used in automotive parts, construction materials, furniture, and textiles. Extraction methods such as retting and mechanical separation are optimized to preserve fiber integrity, while surface treatments enhance fiber-matrix adhesion, ensuring performance and durability in eco-friendly applications.

Oil Palm Empty Fruit Bunches

Oil palm empty fruit bunches (OPEFB), a lignocellulosic byproduct of the palm oil industry, are rich in cellulose (~40 to 50%), hemicellulose (~30%), and lignin (~20%), providing fibers with moderate mechanical properties suitable for biocomposite reinforcement (Ponce *et al.* 2022). OPEFB fibers enhance the strength, durability, thermal insulation, and acoustic absorption of composites, with studies showing improvements in PLA-based composites' thermal resistance and sound dampening capabilities. Despite their moderate tensile strength (typically 100 to 200 MPa), their abundant availability and biodegradability make them a sustainable alternative to synthetic fibers. Processing OPEFB fibers involves drying and chemical treatments, such as alkali or silane modification, to reduce moisture content and improve fiber-matrix adhesion. These fibers are widely used in automotive interior parts, insulation panels, flooring materials, and structural biocomposites, contributing to residue valorization in the palm oil sector while reducing dependence on non-renewable fillers and supporting eco-friendly material development.

Groundnut Shells

Groundnut shells, the outer coverings of peanuts, are rich in cellulose and lignin (~35%) and possess low density, making them ideal lightweight fillers in biopolymer composites (Govindarajan *et al.* 2024). Incorporating 10 wt% groundnut shell powder in epoxy composites has been shown to reduce density by 12% while enhancing acoustic damping, improving thermal and sound insulation properties. These shells are widely used in packaging materials, biodegradable plastics, and lightweight construction applications, offering a renewable alternative to synthetic fillers. However, challenges such as moisture sensitivity and uniform dispersion require surface modifications to optimize performance. Overall, groundnut shells contribute to sustainable development by transforming agricultural residue into high-value materials across multiple industries (Pandey *et al.* 2003; Gurusamy *et al.* (2024).

Table 2 provides approximate values for some key properties of common agricultural residue materials, specifically in the context of their use in biopolymer-based composites. These values can vary depending on the specific processing methods and the source of the material. Table 3 provides the advantages and disadvantages of agricultural residue materials.

Table 2. Common Agricultural Residue Materials: Properties

Agricultural Residue	Cellulose Content (%)	Lignin Content (%)	Hemicellulose Content (%)	Tensile Strength (MPa)	Flexural Strength (MPa)	Water Absorption (%)	Density (g/cm³)
Rice Husk (Kordi *et al.* 2024)	35 to 40	20 to 25	25 to 30	50 to 80	80–120	15–25	1.2–1.4
Cotton Stalk (Prakash *et al.* 2024)	45 to 55	15 to 20	20 to 30	60 to 90	120–150	8–15	1.4–1.6
Sugarcane Bagasse (Miranda *et al.* 2021)	40 to 45	20 to 25	20 to 30	80 to 120	150–200	10–20	1.3–1.5
Wheat Straw (Zhang *et al.* 2022)	30 to 35	20 to 25	30 to 35	40 to 70	100–130	15–25	1.5–1.6
Banana Stem (Kokate *et al.* 2022)	40 to 45	10 to 15	30 to 40	80 to 100	120–160	10–20	1.1–1.3
Coconut Shell (Ajien *et al.* 2023)	40 to 45	25 to 30	20 to 30	70 to 120	120–180	5–10	1.5–1.6
Sisal Leaves (Ajien *et al.* 2023)	60 to 70	8 to 10	15 to 25	150 to 250	200–300	5–15	1.2–1.5
Palm Leaves (Makinde-Isola *et al.* 2024)	40 to 50	15 to 20	20 to 30	70 to 100	150–200	10–15	1.0–1.2
Tamarind Shell (Jayaraman *et al.* 2023)	40 to 50	30 to 40	10 to 15	60 to 90	110–140	10–20	1.4–1.6
Jute Fibers (Song *et al.* 2021)	60 to 70	10 to 15	20 to 30	350 to 550	400–600	10–15	1.3–1.4
Mango Seed Shell (Mohan Kumar *et al.* 2023)	40 to 50	30 to 40	10 to 15	40 to 80	100–130	5–10	1.4–1.5
Olive Pomace (Difonzo *et al.* 2021)	35 to 40	20 to 25	30 to 35	50 to 70	90–130	20–30	1.2–1.4
Coriander Stems (Evon *et al.* 2023)	35 to 40	10 to 15	30 to 40	60 to 80	100–150	15–20	1.1–1.3
Tomato Pomace (Lu *et al.* 2022)	20 to 30	10 to 15	40 to 50	40 to 60	80–110	40–50	1.0–1.2
Almond Shell (Sánchez *et al.* 2022)	30 to 40	30 to 40	20 to 30	60 to 100	120–160	10–15	1.4–1.5
Peanut Shell (Pączkowski *et al.* 2021)	30 to 40	20 to 25	25 to 30	50 to 90	100–130	15–20%	1.4–1.6

Table 3. Common Agricultural Residue Materials: Advantages and Disadvantages

Agricultural Residue	Source	Fiber Extraction Method	Properties	Advantages	Disadvantages
Rice Husk (Kordi *et al.* 2024)	Husk of rice grains	Milling or grinding	Contains silica; low cellulose content	Abundant, low-cost, biodegradable	High silica content; weak fibers for reinforcement
Cotton Stalk (Prakash *et al.* 2024)	Stems of cotton plants	Decortication, mechanical stripping	Cellulose-rich, low lignin	High cellulose content, renewable	Difficult to process, fiber length issues
Sugarcane Bagasse (Miranda *et al.* 2021)	Residue from sugarcane after juice extraction	Mechanical shredding, chemical retting	High cellulose content, good for reinforcement	Abundant, renewable, versatile	High moisture content, low fiber strength
Wheat Straw (Zhang *et al.* 2022)	Stems of wheat plants	Milling, mechanical stripping	Contains cellulose and hemicellulose	Renewable, biodegradable, low-cost	Short fibers, low strength
Banana Stem (Kokate *et al.* 2022)	Stems of banana plants	Mechanical stripping, decortication	High cellulose content, flexible	High cellulose, strong fibers	Fibers can be difficult to extract
Coconut Shell (Ajien *et al.* 2023)	Shells of coconuts	Mechanical grinding, chemical treatment	Dense, lignocellulosic material, high hardness	High density, durable	Difficult to process, limited fiber extraction
Sisal Leaves (Ajien *et al.* 2023)	Leaves of the sisal plant	Decortication, mechanical stripping	Long, strong fibers, good tensile strength	Strong fibers, durable	Expensive extraction, environmental impact
Palm Leaves (Almanassra *et al.* 2024; Makinde-Isola *et al.* 2024)	Leaves of palm trees	Decortication, mechanical stripping	Strong, durable fibers	Strong fibers, biodegradable	Limited commercial processing, expensive
Tamarind Shell (Jayaraman *et al.* 2023)	Hard outer shell of tamarind fruits	Grinding into powder or small pieces	Lignocellulosic, rich in hemicellulose	High availability, cost-effective	Low fiber content, brittle
Jute Fibers (Song *et al.* 2021)	Stems of the jute plant	Decortication, retting	Strong, flexible fibers with good tensile strength	Biodegradable, strong fibers	Sensitive to environmental factors, limited in high-strength composites
Mango Seed Shell (Mohan Kumar *et al.* 2023)	Hard seed shell of mango fruit	Grinding into fine particles	Lignocellulosic material, low fiber content	Abundant residue, biodegradable	Low fiber content, difficult to process
Olive Pomace (Difonzo *et al.* 2021)	Residue from olive oil extraction	Grinding or pressing	Rich in lignin, low in cellulose	High availability, sustainable	Low cellulose content, tough to process
Coriander Stems (Evon *et al.* 2023)	Stems of coriander plants	Mechanical stripping	Low cellulose, high in pectin and hemicellulose	Renewable, biodegradable, low-cost	Low fiber content, weak mechanical properties
Tomato Pomace (Lu *et*	Residue from	Drying and grinding	High moisture content,	Rich in nutrients, eco-	High moisture content,

al. 2022)	tomato processing		low fiber	friendly	low structural integrity
Almond Shell(Sánchez *et al.* 2022)	Outer shell of almonds	Grinding, mechanical shredding	High lignin content, dense	Hard, durable material	Difficult to process, limited use in composites
Peanut Shell (Pączkowski *et al.* 2021)	Outer shell of peanuts	Grinding, mechanical processing	High lignin content, low fiber	Abundant, cost-effective	Low fiber content, brittle material

FACTORS AFFECTING THE DENSITY OF ECO-FRIENDLY BIOCOMPOSITES

Type and Properties of Agricultural Residue Reinforcement

The selection of reinforcement plays a foundational role in determining composite density. Agricultural residues such as rice husk, sugarcane bagasse, groundnut shells, tamarind shell powder, wheat straw, and banana stem fiber have relatively low intrinsic densities (typically 1.2 to 1.4 g/cm³) due to their lignocellulosic structure, which includes voids (Olofsson and Börjesson 2018). Their naturally porous microstructure and hollow cellular arrangement contribute to reduced mass per unit volume. When processed correctly, these fibers can provide adequate mechanical performance at lower weight, making them ideal for environmentally friendly, lightweight structural composites (Petersen, 2008).

Matrix Selection

Bio-based and biodegradable matrices such as PLOH **(**Poly (Lactic acid) Hydroxyapatite**),** starch blends, PBS **(**Polybutylene Succinate), and bio-resins offer lower densities compared to conventional petroleum-derived polymers. These matrices, when paired with light agricultural fillers, help reduce overall composite density (Cardoen *et al.* 2015). For example, a PLOH-groundnut shell composite has been found to have a lower density profile while remaining compostable. The matrix must also exhibit good wetting and interfacial compatibility with the agricultural fibers to minimize void formation and optimize mechanical load transfer—ensuring that weight reduction does not come at the cost of performance (Sommer *et al.* 2015).

Influence of Filler Type, Size, and Loading Content

The use of agricultural powder fillers (*e.g.*, tamarind shell powder, rice husk ash, and coconut shell flour) further enables lightweighting. Finer particles contribute to better packing and dispersion, whereas coarser particles may introduce porosity and affect uniformity (Parveen *et al.* 2024). Using low-density agro-waste fillers instead of mineral fillers (like talc or calcium carbonate) results in environmentally safer and lighter composites (Manickaraj *et al.* 2025).

Fiber-Matrix Interface Engineering and Surface Treatment

The interaction between the fiber and matrix significantly affects the effective density and performance of the biocomposite. Poor bonding may result in delamination or void formation, reducing the material’s weight but also weakening it structurally. Pretreatment methods such as alkaline (NaOH) treatment, silanization, and compatibilizer grafting (*e.g.* maleic anhydride) improve fiber-matrix adhesion, allowing for the use of lower filler loads while maintaining strength (Lozano and Lozano 2018). Effective interfacial engineering enables the creation of more compact, lightweight structures from agricultural waste sources.

Porosity Control and Microstructural Management

In lightweight composite applications, controlled porosity is occasionally purposefully incorporated to decrease weight and enhance thermal or acoustic insulation properties. Uncontrolled voids, which may result from insufficient mixing, inadequate degassing, or suboptimal curing processes, can cause a reduction in density, adversely affecting mechanical integrity (Shapiro-Bengtsen *et al.* 2022). Techniques such as vacuum-assisted resin infusion, high-shear mixing, and particle size control are utilized to reduce undesired porosity. The objective is to minimise mass while ensuring that structural integrity is maintained, thereby preserving the functionality of the intended application (Chandel *et al.* 2025).

Processing Methods Tailored for Lightweight Structures

Processing techniques strongly impact the final density of biocomposites. Foaming, low-pressure compression molding, and extrusion-based processing can introduce designed porosity or optimized fiber orientation to reduce weight (Mohan *et al.* 2024). For structural applications, sandwich constructions, cellular or honeycomb core designs, and layered laminates using agro-based materials provide high stiffness-to-weight ratios (Parveen *et al.* 2024). These methods are widely used to fabricate structural panels, acoustic boards, and eco-friendly packaging for new-generation building and transport applications.

Moisture Sensitivity and Hygroscopic Behavior

Most agricultural fibres exhibit hygroscopic properties, indicating their ability to absorb moisture from the atmosphere. This absorption results in a temporary increase in weight and can impact dimensional stability. Mitigation of this behaviour can be achieved through the implementation of fiber pre-drying, application of surface coatings, or selection of a hydrophobic matrix (Karuppusamy *et al.* 2025). In lightweight applications where moisture control is essential, such as transportation interiors or construction boards, this factor directly influences consistent density and long-term performance.

Hybridization and Structural Design

Hybrid composites, which are formed by the integration of multiple types of natural fibres or agro-waste fillers, can demonstrate enhanced mechanical strength while maintaining a reduced weight. Combining banana fibre with tamarind shell powder has been shown to result in a material that exhibits improved strength and thermal stability while maintaining a consistent mass (Aruchamy *et al,* 2025). The implementation of bio-architectures, including grid structures, foam-filled cavities, and thin-walled laminates, facilitates weight reduction while satisfying load-bearing specifications. The application of these principles is evident in sustainable construction elements, automotive panels, and green consumer goods (Patel and Patel 2021).

PROCESSING OF BIOPOLYMER-BASED COMPOSITES

Fiber Separation and Preparation

The separation and preparation of natural fibers are pivotal in defining the performance and reliability of biopolymer-based composites. The quality, morphology, and surface chemistry of the isolated fibers strongly influence fiber–matrix adhesion, mechanical reinforcement efficiency, and overall composite durability. Therefore, optimized extraction methods tailored to the fiber type and end-use requirements are essential to balance preservation of fiber integrity with enhancement of interfacial compatibility.

Mechanical methods

Mechanical techniques such as decortication and milling are commonly employed for their scalability and cost-efficiency in large-scale fiber processing. Decortication physically separates fibers from plant stalks through crushing, scraping, or beating, carefully preserving fiber length and aspect ratio, key parameters that directly affect tensile strength and load transfer within composites. The retention of fiber length during decortication supports the formation of continuous load paths in composites, critical for high-strength applications (Nagarajan *et al.* 2020). However, mechanical methods may introduce surface defects or fibrillation, which can either be beneficial by increasing surface roughness for adhesion or detrimental by reducing fiber strength if excessive damage occurs. Milling, by contrast, reduces biomass to short fibers or powder, facilitating uniform dispersion in polymer matrices but sacrificing fiber aspect ratio and reinforcing potential. This trade-off must be judiciously managed based on composite design goals.

Chemical methods

Chemical treatments, particularly alkali (NaOH) treatments, play a vital role in refining fiber surfaces by selectively removing amorphous, non-cellulosic components such as lignin, hemicellulose, pectins, and natural waxes. This process increases surface roughness and exposes hydroxyl groups on cellulose, substantially improving wettability and interfacial bonding with hydrophobic polymer matrices (Vinod *et al.* 2023). Alkali treatment also disrupts hydrogen bonding within fiber bundles, reducing aggregation and enhancing fiber dispersion during composite fabrication. However, the severity of chemical treatment must be controlled to avoid excessive cellulose degradation or fiber embrittlement, which compromise mechanical performance. The removal of lignin and hemicellulose can also reduce fiber moisture absorption tendencies, thereby improving dimensional stability and environmental resistance of composites. Moreover, chemical treatments can modulate thermal stability by eliminating lower-decomposition-temperature components, expanding processing windows for thermoplastic or thermoset composites.

Biological methods

Enzymatic treatments offer a highly selective and eco-friendly alternative for fiber extraction, employing enzymes such as laccase to degrade lignin and xylanase to hydrolyze hemicellulose, while preserving the crystalline cellulose backbone (Palaniappan *et al,* 2024b). This precision minimizes damage to fiber microstructure, maintaining mechanical integrity and natural polymerization degrees. Additionally, enzymatic methods reduce chemical residue and energy consumption compared to harsh chemical processes, aligning with sustainable manufacturing principles. However, these processes are slower and involve higher costs due to enzyme specificity and reaction time constraints, limiting their applicability to high-value composites or specialty applications. Ongoing research into enzyme immobilization, synergistic enzyme cocktails, and process intensification aims to improve scalability and economic viability, as shown in Table 4.

Table 4. Comparison of Fiber Separation Methods

Criteria	Mechanical Methods	Chemical Methods	Biological Methods
Cost	Low initial cost, but may require energy-intensive processes	Moderate to high, due to chemicals and equipment	Moderate, due to enzyme production costs
Processing Speed	Fast, suitable for mass production	Moderate, depending on the chemical process	Slow, due to enzyme reaction times
Environmental Impact	Low, minimal chemical use	High, due to chemical residue and environmental concerns	Low, more eco-friendly and sustainable
Fiber Quality	Lower, may need further treatment for high-quality fibers	High, better bonding with polymers	High, preserves fiber integrity and purity
Suitability for High-Performance Composites	Moderate, suitable for less demanding applications	High, suitable for demanding, high-performance composites	High, especially for eco-friendly and sustainable products
Scalability	Highly scalable, well-suited for large-scale operations	Scalable, but more expensive for large quantities	Limited scalability due to slower process and higher costs

COMPOSITE FABRICATION TECHNIQUES FOR LIGHTWEIGHT BIOCOMPOSITES

To develop truly lightweight bio composites, fabrication methods must move beyond conventional approaches that emphasize dense, void-free structures. High matrix saturation typically negates the natural low-density advantages of agricultural residues. Instead, effective strategies as listed below prioritize minimal binder content, controlled porosity, and structural efficiency.

1. **Discontinuous Binder and Foamed Systems:** Low-density composites can be achieved by limiting the polymer to a discontinuous binder phase, where the matrix acts only as an adhesive rather than filling all internal voids. This helps preserve the lumen spaces in fibers and reduces overall mass (Palaniappan *et al.* 2024a). Foamed biopolymers, produced using physical or chemical blowing agents, further enhance weight reduction by introducing microcellular structures while maintaining load-bearing capacity.

2. **Adhesive Coating and Thermal Pressing:** Another promising technique involves light adhesive coating of agricultural residues, followed by thermal pressing. This approach compacts the material into a cohesive form using minimal binder, often aided by the natural lignin content acting as a thermoplastic at elevated temperatures. This approach is particularly suitable for panel products made from shells, husks, and fibers (Reis *et al.* 2011).

3. **Layered and Sandwich Structures:** Hybrid fabrication strategies such as sandwich structures utilize low-density biomass cores with stiffer outer layers to balance mechanical strength and reduced weight. This configuration maintains structural performance while minimizing overall material usage (Palanisamy *et al.* 2022a).

SURFACE TREATMENTS

Enhancing the fiber–matrix interface is paramount to maximize load transfer and composite longevity, as natural fibers inherently possess hydrophilic surfaces that poorly bond with typically hydrophobic polymer matrices. Surface modification techniques aim to alter fiber chemistry and morphology to improve adhesion, moisture resistance, and thermal stability.

Alkali Treatment

Alkali treatment employs dilute sodium hydroxide solutions to remove surface impurities such as lignin, hemicellulose, waxes, and oils. This results in increased fiber surface roughness and exposure of cellulose microfibrils, effectively increasing the number of accessible hydroxyl groups available for bonding (Sumesh and Kanthavel 2020). The treatment also enhances crystallinity by reducing amorphous regions, which improves mechanical integrity and resistance to microbial attack. Alkali-treated fibers exhibit improved wettability and interfacial adhesion, which translates into composites with superior tensile strength and reduced moisture-induced swelling. However, overexposure to alkali can cause cellulose degradation, reducing fiber strength, necessitating precise control of treatment concentration and duration.

Silane Coupling Agents

Silane coupling agents chemically bridge the hydrophilic natural fiber surface and the hydrophobic polymer matrix by forming covalent bonds on both ends. The hydrolysable alkoxy groups on the silane react with cellulose hydroxyls, while the organofunctional groups interact with the polymer chains, thus enhancing fiber–matrix compatibility (Mishra and Naik 2005). This dual reactivity reduces interfacial voids and inhibits moisture absorption, leading to composites with improved mechanical strength, thermal stability, and environmental durability. Silane treatment also imparts improved resistance to hydrothermal aging and fungal degradation. Optimization of silane type and application method is crucial to achieving maximal interfacial enhancement without compromising fiber integrity.

APPLICATIONS OF LIGHTWEIGHT BIOPOLYMER COMPOSITES

Figure 7 demonstrates the diverse applications of lightweight biopolymer composites derived from agricultural residue biomass. The subsequent subsections outline the application domains and the fundamental strategies employed to attain lightweight composite performance, which include fiber-matrix optimization, structural design, and material hybridization.

Automotive Industry

In the automotive sector, weight reduction is directly linked to fuel efficiency and emission control, especially under stringent global environmental regulations. Biopolymer composites reinforced with jute, flax, or kenaf and bound in matrices such as PLA or PHA reduce component weight by up to 40% compared to glass fiber composites (Dwivedi and Mishra 2019; Vinoth *et al.* 2024). To maintain structural performance while lowering density, manufacturers adopt hybrid reinforcements, foamed polymer matrices, and laminated sandwich structures. These strategies enable the development of lightweight dashboards, door panels, and trims that offer both impact resistance and energy absorption, particularly beneficial in electric vehicles (Pączkowski *et al.* 2021; Prakash 2022).

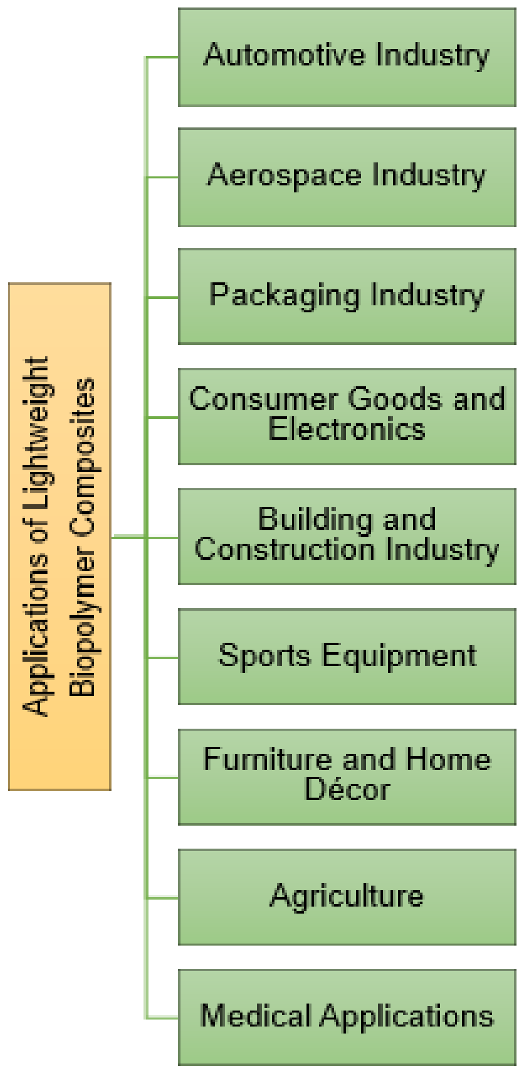

Fig. 7. Applications of biopolymers

Aerospace Industry

Aerospace applications demand high stiffness-to-weight ratios, and lightweight biopolymer composites fulfill this need in cabin interiors and secondary structures. Components such as tray tables, seat shells, and panels benefit from microcellular foaming and layered biofiber design for strength without density penalties. Natural fibers offer superior thermal and acoustic insulation, while controlled porosity and interface engineering enhance dimensional stability and vibration damping (Ain *et al.* 2016; Glińska *et al.* 2021). Advanced treatments reduce moisture sensitivity and improve durability in harsh environments (Devadiga *et al.* 2020; Chaturvedi *et al.* 2022).

Packaging Industry

Packaging applications rely on composites that are both lightweight and biodegradable. Composites made from sugarcane bagasse, rice husks, and wheat straw are processed into low-density trays, containers, and films using techniques like compression molding and foaming agents. These products offer sufficient barrier strength and thermal stability while reducing plastic waste (Dele-Afolabi *et al.* 2018; Chithra *et al.* 2024). Tailoring fiber loading and particle size allows optimization of rigidity and moisture barrier performance, making them suitable for food, pharmaceutical, and consumer packaging (Sivasubramanian *et al.* 2021).

Consumer Goods and Electronics

In electronics, product miniaturization demands lightweight yet durable enclosures. Biopolymer composites with agro-waste fillers are used in protective casings, earbuds, and accessories. Strategies such as thin-wall molding, fiber surface modification, and multi-phase reinforcement help achieve lightweight performance along with heat resistance and impact strength (Madurwar *et al.* 2013; Yadav *et al.* 2021). These solutions meet circular economy goals and address growing concerns over e-waste and recyclability (Nithyanandhan *et al.* 2022).

Building and Construction Industry

Lightweight biopolymer composites are replacing heavier, carbon-intensive materials in panels, partitions, and insulation boards. Materials such as coir, hemp, and flax—combined with bio-based matrices—are engineered into sandwich panels, hollow core structures, and laminates to reduce density while retaining load-bearing capacity. Their high thermal resistance, low conductivity, and minimal embodied energy contribute to sustainable building design (Rai *et al*. 2021; Nagappan *et al.* 2022). Enhanced resistance to moisture and microbial attack makes them suitable for both interior and semi-structural applications (Kurien *et al*. 2023; Manickaraj *et al.* 2023).

Sports Equipment

In sports, performance gear including bicycles, skis, and paddles demand materials that combine lightness with stiffness and toughness. Biopolymer composites achieve this balance through unidirectional natural fiber reinforcements, optimized layering, and resin modification. The reduction in weight enhances user performance while minimizing fatigue. In textiles, hemp and cotton stalk fibers improve breathability and biodegradability, reducing synthetic microplastic pollution in athletic wear (Gheorghita *et al.* 2021; Das *et al.* 2023).

Table 5. Agricultural Residue Materials, Potential Applications, and Properties

Agricultural Waste	Composition	Potential Applications	Properties
Rice Husk (Kordi *et al.* 2024)	High in silica, cellulose, and lignin	Composites, biofuels, and insulation materials	High thermal resistance, light weight
Cotton Stalk (Prakash *et al.* 2024)	Cellulose, hemicellulose, lignin	Fiber-reinforced composites, paper, and textiles	Good mechanical strength, biodegradable
Sugarcane Bagasse (Miranda *et al.* 2021)	Cellulose, hemicellulose, lignin	Bioplastics, fiberboards, and insulation materials	High cellulose content, thermal stability
Wheat Straw (Zhang *et al.* 2022)	Cellulose, hemicellulose, lignin	Biocomposites, particleboards, and biofuels	Moderate strength, biodegradable
Banana Stem (Kokate *et al.* 2022)	Cellulose, hemicellulose, lignin	Fiber-reinforced composites, textiles, and paper	High strength-to-weight ratio, biodegradable
Coconut Shell (Ajien *et al.* 2023)	Cellulose, lignin, and other extractives	Activated carbon, composite filler, and biofuels	High hardness, excellent for composites
Sisal Leaves (Ajien *et al.* 2023)	Cellulose, lignin, and hemicellulose	Biocomposites, rope, and textiles	High mechanical strength, biodegradable
Palm Leaves (Makinde-Isola *et al.* 2024)	Cellulose, hemicellulose, lignin	Biocomposites, handicrafts, and textiles	Flexible, lightweight, biodegradable
Tamarind Shell (Jayaraman *et al.* 2023)	Cellulose, lignin, hemicellulose	Composites, biochar, and adsorbents	High carbon content, thermal stability
Jute Fibers (Song *et al.* 2021)	Cellulose, lignin, and hemicellulose	Biocomposites, packaging, textiles, and insulation materials	High tensile strength, biodegradable
Mango Seed Shell (Mohan Kumar *et al.* 2023)	Lignin, cellulose, hemicellulose	Biocomposites, activated carbon, and biofuels	High lignin content, excellent for composites
Olive Pomace (Difonzo *et al.* 2021)	Cellulose, lignin, and olive oil extract	Biocomposites, biofuels, and bioplastics	High oil content, good for bio-based applications
Coriander Stems (Evon *et al.* 2023)	Cellulose, hemicellulose, lignin	Paper, textiles, and composites	Biodegradable, flexible
Tomato Pomace (Lu *et al.* 2022)	Cellulose, pectin, hemicellulose	Biocomposites, food packaging, and biodegradable films	High moisture content, biodegradable
Almond Shell (Sánchez *et al.* 2022)	Cellulose, lignin, hemicellulose	Composites, filler for plastics, and energy production	High hardness, good for composite fillers
Peanut Shell (Pączkowski *et al.* 2021)	Cellulose, lignin, and hemicellulose	Composite filler, biofuels, and activated carbon	High lignin content, good for fillers

Furniture and Home Décor

Furniture applications benefit from composites that are structurally durable, aesthetically pleasing, and lightweight. Agricultural residues such as jute and flax are used to fabricate molded, thin-walled panels and hollow-core furniture elements. Such design strategies reduce material usage and weight while preserving strength and form (Udayakumar *et al.* 2021; Samir *et al.* 2022; Sathesh Babu *et al.* 2024). These materials also support sustainable interior design, aligning with consumer preferences for natural aesthetics and eco-conscious living.

Agriculture

Biopolymer composites serve eco-friendly roles in agriculture through biodegradable mulching films, seedling pots, and fertilizer-release trays. Lightweight formulations are developed using foam extrusion and low-pressure molding, making the products easy to handle and transport (Joshi *et al.* 2020; Gowda *et al.* 2023). Agricultural waste-derived composites such as banana fiber and rice husk offer both nutrient release and soil compatibility while minimizing plastic contamination (Udayakumar *et al.* 2021).

Medical Applications

In medicine, biopolymer composites are applied in temporary implants, surgical tools, and wound dressings. These products must be lightweight, biocompatible, and mechanically stable. Porosity control, resorbable matrix selection, and nanofiber integration allow tuning of degradation rates and mechanical strength for specific applications (Wu *et al.* 2021). Lightweight surgical tools made from such composites offer ergonomic benefits and reduce environmental impact from single-use plastics (Baranwal *et al.* 2022; Udayakumar *et al.* 2021).

Applications and properties of various agricultural residues are listed in Table 5.

END-OF-LIFE STRATEGIES AND CIRCULAR ECONOMY

Integrating end-of-life (EoL) strategies into the design and use of biopolymer-based composites is critical to achieving circular economy goals. These strategies aim to minimize environmental impact and maximize resource recovery at the end of a product's lifecycle. Agricultural residue-derived composites, while inherently eco-friendlier due to their renewable and biodegradable nature, require well-defined EoL pathways to fully realize their sustainability potential (Parveen *et al.* 2024).

Common EoL strategies for such composites include:

1. *Biodegradation and Composting:* Composites made entirely from biodegradable matrices (*e.g*., PLA, PHB) and natural fillers like rice husk, coconut shell, or wheat straw can undergo microbial degradation under industrial composting conditions. However, biodegradation rates depend heavily on matrix type, filler treatment, and environmental conditions (Sumesh *et al.* 2023; Manickaraj *et al.* 2025).
2. *Mechanical and Chemical Recycling:* When biocomposites contain thermoplastic matrices, mechanical recycling through reprocessing and remolding can be viable, although the presence of natural fibers may alter melt flow properties. Chemical recycling techniques are still in early development stages for bio-based systems and

may not yet be widely scalable (Lozano and Lozano 2018).

3. *Thermal Recovery (Incineration with Energy Recovery):* For composites that are not biodegradable or recyclable, controlled incineration can offer energy recovery. However, this strategy must be used cautiously due to potential emissions, especially when mixed with synthetic polymers (Shapiro-Bengtsen *et al.* 2022).
4. *Landfilling:* Though not encouraged in a circular framework, landfilling remains a common route in the absence of infrastructure for recycling or composting. Biocomposites with high natural content are less harmful in landfills compared to petroleum-based counterparts but still represent a loss of valuable resources (Chandel *et al.* 2025).

To support circularity, future design should incorporate design-for-disassembly, modular structures, binder-free processing, and mono-material systems to simplify separation and recovery. Moreover, the use of bio-based, non-toxic additives and surface treatments enhances biodegradability and EoL flexibility (Mohan *et al.* 2024). A dedicated focus on these strategies supported by literature on life cycle assessments (LCAs), biodegradability studies, and recycling technologies ensures that biocomposites not only reduce the environmental footprint during use but also remain environmentally benign after disposal (Parveen *et al.* 2024). This approach fosters material circularity, reduces dependence on virgin raw materials, and contributes to closing the material loop in line with global sustainability frameworks such as the EU Green Deal and UN SDGs (Karuppusamy *et al.* 2025).

CONCLUSIONS

The development of biopolymer-based composites from agricultural residue biomass presents a viable pathway toward sustainable, lightweight materials suitable for eco-friendly structural applications, particularly in the construction sector. This review has demonstrated the potential of underutilized residues such as rice husk, corn stalks, wheat straw, and banana fibers to serve as cost-effective and renewable reinforcements or fillers when combined with biodegradable polymer matrices.

1. The use of agricultural residues derived biocomposites strongly aligns with circular economy principles by valorizing waste streams into high-value materials while reducing environmental burdens. By tailoring fiber type, content, and processing methods, these composites can be optimized for diverse applications in automotive, packaging, building materials, and other industries where sustainability and reduced weight are critical requirements.
2. Despite notable advancements, challenges remain in ensuring uniform composite quality, enhancing interfacial bonding, and scaling up manufacturing processes economically. Future research must focus on improving fiber–matrix compatibility, optimizing mechanical and thermal performance, and addressing long-term durability. Additionally, comprehensive assessments of techno-economic feasibility and lifecycle performance are necessary to support broader commercial adoption.
3. A critical aspect of advancing sustainability is addressing end-of-life (EoL) strategies. These include industrial composting for fully biodegradable composites, mechanical

or chemical recycling of matrix–fiber systems, and energy recovery through incineration when composting is not feasible. Incorporating such strategies from the design phase enables a closed-loop lifecycle, enhancing the material's contribution to the circular economy. Increased emphasis on recyclable formulations, binder-free systems, and bio-based adhesives can further support circular material flows.

4. Biopolymer composites offer a promising route to reduce reliance on petroleum-based materials across multiple sectors including automotive, aerospace, construction, electronics, and healthcare. Their low carbon footprint, renewable origin, and biodegradability make them ideal candidates for green manufacturing and sustainable product development. As global interest in circular design intensifies, these materials are poised to become central to next-generation eco-conscious technologies.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

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