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Research Article

Renewable Composites for Sustainable and ECO-Friendly Solutions

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Abstract

The planet faces a polycrisis - a set of interconnected challenges that include climate change, biodiversity loss, and resource depletion. These issues are not isolated but are symptoms of unsustainable practices. Ignoring them risks catastrophic consequences for the environment, society, and economies worldwide. This paper examines innovative approaches to developing biodegradable composite materials that are environmentally friendly. By using renewable resources and advanced methods, these composites improve strength while being eco-friendly. The study shows how biodegradable composites can help reduce plastic waste and support sustainability in different industries, tackling major global environmental issues. Renewable composites are usually made from biodegradable materials like polylactic acid (PLA) or polyhydroxyalkanoates (PHA) mixed with natural fibers such as jute or flax. They aim to lower environmental impact while still performing well. New processing techniques help make these materials more efficient and reduce waste during production. Industries like aerospace and automotive are starting to use these lightweight and recyclable materials, which helps create a circular economy. However, challenges remain in increasing production and keeping costs low. To promote the use of renewable composites and ensure a sustainable future, ongoing research and collaboration among industry players are essential.

Keywords

Renewable Composites, Sustainability, Biodegradable Materials, Natural Fibers, Recycling Technologies, Eco-Friendly Innovations

1. Introduction

Humanity is currently confronting a polycrisis, marked by the simultaneous escalation of climate change, biodiversity loss, and resource depletion. These systemic challenges are largely driven by unsustainable patterns of industrial production and consumption, particularly the widespread use of fossil-derived, non-biodegradable materials. In this context, biodegradable and renewable composite materials have emerged as a promising class of sustainable alternatives. Engineered from natural fibers and bio-based polymers, these composites are designed to reduce dependence on petroleum-based resources, minimize waste, and lower carbon emissions throughout their life cycle.

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1.1. Structural Elements of Bio-Composites

1.1.1. Bio-Based Polymers (Matrices)

The matrix phase in renewable composites typically consists of biodegradable polymers synthesized from renewable feedstocks. The most widely used bio-polymers include:

Polylactic Acid (PLA): Derived from starch-rich crops such as corn or sugarcane; offers good mechanical strength and compostability.

Polyhydroxyalkanoates (PHA): Bacterially synthesized; highly biodegradable under natural conditions.

Polybutylene Succinate (PBS): A biodegradable polyester with moderate thermal stability.

Starch-Based Polymers: Economical and compostable but often require blending for enhanced performance.

Cellulose Acetate: A derivative of cellulose with improved thermoplasticity and biodegradability.

1.1.2. Natural Fiber Reinforcements

Natural fibers serve as reinforcements within the polymer matrix, improving strength, stiffness, and reducing weight. Commonly utilized fibers shown in Table 1 include:

Flax - Good balance of stiffness and biodegradability. High water absorption limits outdoor use.

Hemp – Strong thermal and mechanical stability. Suitable for structural applications.

Jute - Economical with moderate strength. Partially biodegradable matrix.

Kenaf – Sustainable matrix. Moderate recyclability. High bio-fiber availability.

Coir – Good biodegradability. Low mechanical strength and high moisture uptake.

Ramie – High strength and recyclability through chemical vitrimer networks.

Bamboo – Lightweight and renewable. PLA limits heat resistance.

These fibers are characterized by low density (1.2–1.6 g/cm³), renewable origin, and biodegradability.

***Table 1.** Quantitative data of various composites.*

Composite Type	Fiber Volume (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Density (g/cm^3)	Water absorption (% over 24 h)	Thermal stability (°C)	Bio-degradability	Re-cyclability
Flax/PLA	30–40%	60–80	6–10	1.3-1.5	8-12%	170	Yes	Yes (Thermal)
Hemp/Amino-Silane Epoxy Vitrimer	35–45%	75–100	6–9	1.4-1.6	6-8%	220	Yes	Yes (Low-temp)
Jute/Polypropylene	25–35%	40–60	3–5	1.2-1.4	5-9%	180	Partial	Limited
Kenaf/Bio-Epoxy	30-40%	65-85	6-9	1.3-1.5	6-10%	200	Yes	Yes (partial thermal)
Coir/Polycaprolactone (PCL)	20-30%	30-50	2-4	1.1-1.3	10-14%	160	Yes	Limited
Ramie/Polyimine Vitrimers	30–40%	70–90	7–11	1.3-1.5	6-10%	200	Yes	Yes (Chemical)
Bamboo/PLA	30-40%	55-70	5-8	1.2-1.4	7-11%	170	Yes	Yes (Thermal)

Composites such as hemp/epoxy vitrimer and ramie/polyimine vitrimer demonstrate high tensile strengths (75–100 MPa and 70–90 MPa respectively), making them suitable for load-bearing applications. Higher values, as observed in flax/PLA and ramie-based composites (6–11 GPa), suggest these materials maintain shape under stress, which is vital for structural stability. Density values, typically ranging from 1.1 to 1.6 g/cm³, influence the weight and fuel efficiency of components in sectors like automotive and aerospace. Lower densities, such as in coir/PCL composites (1.1–1.3 g/cm³), enable lightweight design but often at the cost of mechanical strength. Water absorption data, expressed as a percentage increase in weight after 24 hours, signifies the material's hydrophilicity. Composites with higher absorption, like coir and flax-based ones (up to 14%), may face degradation in humid or outdoor conditions unless treated or coated. Thermal stability determines the processing and application limits of these materials, with vitrimer-based composites showing higher degradation thresholds (~200–220℃), enabling broader industrial use. Biodegradability indicates whether a material can naturally decompose without harming the environment. Most composites in the table are biodegradable due to their natural fibers and bio-based matrices. Recyclability, whether thermal or chemical, is essential for circular economy models. Vitrimers, for example, enable reprocessing via chemical bonds, while PLA-based systems allow thermal reshaping.

Overall, the data reflect a trade-off between sustainability and performance: while biodegradable composites offer eco-friendly solutions, further optimization is needed in mechanical strength, water resistance, and recyclability to fully replace traditional synthetic materials in demanding industrial applications.

1.2. Green Composites in Industry & Environment

Renewable composites are increasingly utilized in sectors such as:

1) Automotive: Interior panels, door trims (e.g., Mercedes-Benz uses flax-based panels)
2) Aerospace: Lightweight, sustainable alternatives to carbon fiber for secondary structures
3) Construction: Panels, insulation, and decorative elements
4) Packaging: Biodegradable containers and films
5) Consumer Goods & Sports: Helmets, bicycles, and casing materials

Their adoption is motivated by regulatory pressures (e.g., EU-European Union plastics directives), reduced environmental footprints, and cost-effectiveness.

1.2.1. Advantages of Biodegradable Natural Fiber Composites (NFCs)

Compared to synthetic fiber composites (e.g., glass or carbon fiber), the following advantages of NFCs in Table 2 make them suitable for eco-conscious applications, especially where end-of-life recyclability and lifecycle emissions are critical.

Table 2. Natural Fiber Composite (NFCs) versus Synthetic Composites.

Property	Natural Fiber Composite	Synthetic Composites
Density (g/cm^3)	1.2-1.5	1.8-2.5
Carbon Footprint (kg CO_2/kg composite)	0.25-0.5	2-5
Biodegradability	Yes	No
Specific Strength	High due to lower density	Very High
Energy Requirement (kWh/kg)	1.5-3	25-75
Renewable Feedstock	Yes	No
Recyclability	Limited but improving	Often complex and energy-intensive
Cost	20-50% lower	High due to processing requirements

1.2.2. Biodegradable Composite Materials: Addressing Plastic Waste

The integration of natural fibers with biodegradable polymers offers a viable route to replacing traditional plastics. These materials:

1) Decompose naturally via microbial and environmental action.
2) Alleviate microplastic pollution.
3) Retain mechanical integrity suitable for structural and semi-structural applications.
4) Enhance compatibility with biological systems, reducing toxicity and landfill burden.

Recent studies have demonstrated that flax/PLA composites, for example, can retain tensile strengths of 60–80 MPa and biodegrade within 90–180 days in industrial composting environments.

2. Literature Review

Over the past fifty years, composite materials have rapidly evolved and expanded beyond aerospace and defense, becoming widely used in various industries. Their versatility allows for improved product quality and cost-effectiveness, making them a popular choice for achieving high structural performance. Composites offer benefits such as high performance, low weight, and compliance with environmental regulations, making them increasingly prevalent in everyday applications [1-4]. Composites were created to enhance the strength and stiffness of traditional materials that couldn't be improved otherwise [1-3]. Composite materials are complex systems made of two or more components that enhance each other's properties, resulting in superior performance. They consist of a matrix, which shapes and protects the fibers, and reinforcement, which provides strength and rigidity. The interaction between these phases is crucial, as their combined characteristics define the final product's mechanical properties [1-4]. Sustainable development requires rational industrial solutions, eco-products, and advanced recycling technologies to manage waste and critical materials effectively. This includes substituting critical materials and creating lightweight structures for intelligent resource use [3, 4]. Despite the potential of bio-based and biodegradable polymers, their high cost and limited properties hinder their widespread application [3]. The article aims to develop high-performance biodegradable composite materials using natural and recycled fibers, focusing on various polymer matrices and textile reinforcements that meet ecological standards, suitable for applications in industries like automotive [5].

Natural fiber-reinforced polymer composites have been used in the automotive industry since 1941, with major manufacturers like Ford, Mercedes-Benz, Audi, and Toyota adopting bio-based composites in various applications [6]. The mechanical properties of biodegradable composites depend on the volume fraction of fibers used, affecting their tensile strength and modulus [7]. Laria et al. studied the mechanical properties of recycled LDPE-HDPE (low density polyethylene-high density polyethylene) and PET (polyethylene terephthalate) composites for building components, finding their strength to be about 60% that of virgin materials in tensile, flexural, and compressive tests [8]. This paper addresses the reliance on petroleum in polymer production by exploring biopolymers combined with biosensors, emphasizing their properties, applications, and environmental benefits. It highlights the potential of renewable biopolymers in various fields, their biodegradability, and their use in developing sensitive chemical sensors for medical and environmental applications [9]. Thermoplastics are categorized into crystalline, semicrystalline, and amorphous types, with crystalline polymers like HDPE, LDPE, and PP (polypropylene) exhibiting ordered arrangements for better impact performance. In contrast, amorphous thermoplastics, such as PMMA (polymethyl methacrylate), PVC (poly vinyl chloride), PPSU (polyphenylsulfone), PC (polycarbonate), and ABS (acrylonitrile butadiene styrene), have randomly arranged molecular chains [10, 11].

Monteserin et al. developed eco-friendly epoxy vitrimers using a Schiff base from a petroleum-derived diamine (DDM: 4,4'-Diaminodiphenylmethane), vanillin, and linseed oil-derived epoxy resin. These vitrimers can be reprocessed and recycled under mild conditions [12]. Mingen et al. created hemp-based, recyclable composites with enhanced fiber-matrix adhesion by incorporating amino silane into a dual-network vitrimer matrix, allowing for low-cost recycling via aminolysis [13]. Ali et al. produced flax-fiber vitrimers that showed superior interfacial shear strength (20.0 MPa) compared to standard epoxy (11.8 MPa) and demonstrated effective low-temperature repair methods [14]. Li et al. investigated ramie-yarn-reinforced polyimine vitrimers, which exhibited excellent self-healing and water-barrier properties, maintaining performance even after nine recycling cycles [15]. The durability of sustainable biobased composites has gained significant attention due to the rising demand for environmentally friendly alternatives to conventional materials. According to the review (2020), the water absorption of natural fiber composites can reach up to 15% by weight, leading to swelling, micro-cracking, and reduced interfacial bonding, especially under cyclic weathering conditions [16]. Maiti et al. (2022) emphasized that fiber–matrix adhesion, environmental exposure, and fiber degradation are key challenges affecting the long-term performance of natural fiber-reinforced composites. Their review highlights that while such composites demonstrate promising mechanical strength and low environmental impact, exposure to moisture and UV radiation significantly reduces their structural integrity over time, necessitating surface treatments and hybrid reinforcement techniques to enhance durability [17]. Recent findings by Afroj et al. (2024) further support this, noting that incorporating nano-fillers and biodegradable polymers can enhance thermal and moisture resistance while maintaining biodegradability [18]. Meanwhile, the 2023 review reports a steady increase in global research focused on enhancing life-cycle performance, citing a 35% rise in publications between 2018 and 2022 on biobased composite longevity [19]. Additionally, the 2021 study stresses the importance of end-of-life considerations such as recyclability and compostability, often overlooked in durability studies [20]. A Review conducted in 2023 identifies the lack of standardized testing for long-term durability under real-world conditions as a major barrier to widespread adoption [21]. Collectively, these studies underline the need for integrated strategies combining material innovation, protective treatments, and standardized durability assessments to realize the full potential of sustainable biobased composites.

2.1. Classification of References

Primary Sources: Original research articles, experimental data, and case studies.

Secondary Sources: Reviews, meta-analyses, and theoretical papers.

Tertiary Sources: Encyclopedias, textbooks, and databases summarizing primary and secondary sources.

The research papers (Table 3) are organized based on their year of publication, categorizes them into research areas, highlights their impact, and outlines their future scope.

Table 3. *Research papers significance.*

Year	Title	Area	Impact	Future Scope
1983	Composite Materials Handbook	Composite Materials	Foundational Reference	Material Science Applications
1989	Fundamentals of Composites Manufacturing	Manufacturing	Industry Standard	Advanced Manufacturing Techniques
2014	Green Composites	Sustainability	Emerging research	Eco-friendly materials
2016	Materials Selection in Automotive Industry	Automotive Engineering	Efficiency Improvement	Lighter and Safer Vehicles
2018	New Composite Materials	Biodegradable Composites	Waste Reduction	Sustainable Textile Recycling
2023	Green Composite Materials and Applications	Green Composites	Environmental Impact	Sustainable Chemical Processes
2023	Natural Fibers and Their Composites	Eco-Friendly Materials	Alternative to Conventional Materials	Reduced Carbon Footprint
2023	Recycled PET and LDPE-HDPE Composites	Recycling	Waste Management	Building Applications
2022	Biopolymer Composites with Sensors	Smart Composites	Medical and Environmental Use	Advanced Biopolymers
2023	Pyrolysis of Charring Composite Materials	Fire Safety	Material Degradation Studies	Improved Fire Resistance
2022	Sustainable Recycling Technologies	Recycling	Circular Economy	Next-Gen Recycling Tech
2023	Sustainable Biobased Epoxy Thermosets	Biobased Polymers	Green Composite Development	Renewable Polymer Chemistry
2024	Hemp Fiber Reinforced Biocomposites	Bio-based Composites	Sustainable Development	Vitrimer Applications
2022	Aligned Discontinuous Flax Fibre Composites	Sustainable Composites	Repair and Performance	Advanced Fiber Composites
2023	High Performance Ramie Yarn Composites	Recyclable Composites	Eco-Friendly High-Performance Materials	Improved Polymer Chemistry
2020	Durability of Sustainable Biobased Composites	Sustainability	Longevity Studies	Sustainable Infrastructure
2022	Sustainable Fiber-Reinforced Composites	Composite Materials	Material Strength and Sustainability	Green Engineering
2024	Innovative Eco-Friendly Bio-Composites	Bio-Composites	Holistic Review	Future Sustainability Trends
2023	Sustainability Trends in Composite Materials	Sustainability	Current Market Trends	Industrial Adoption
2021	Green Composites and Sustainability	Sustainability	Eco-Friendly Development	Environmental Benefits
2023	Sustainable Composites: Critical Questions	Sustainability	Structured analysis of current advancements and limitations	Next-Gen Innovations for efficient end-of-life strategies

2.2. Observations

The paper emphasizes the role of biodegradable composites in addressing interconnected global crises such as climate change, biodiversity loss, and resource depletion. Key impacts include:

i. Natural fiber composites (NFCs) offer advantages like biodegradability, low density, and cost-effectiveness compared to synthetic fibers.
ii. Life cycle assessments (LCA) show that biocomposites have lower environmental impacts than traditional petrochemical-based composites.
iii. Reduction in Plastic Waste: Biodegradable composites help mitigate plastic pollution by replacing traditional polymers with eco-friendly alternatives like polylactic acid (PLA) and natural fibers such as jute and flax.
iv. Carbon Footprint Reduction: The use of renewable materials lowers greenhouse gas emissions compared to synthetic composites.
v. Support for Circular Economy: Innovations in recycling technologies and material design promote reusability and sustainability across industries like automotive and aerospace.
vi. Resource Conservation: By using agricultural by-products and bio-feedstocks, these materials reduce reliance on finite resources.

2.3. Findings

a) *Material Properties:* Bio-composites reinforced with plant fibers exhibit good mechanical properties but may require surface treatments for improved durability.
b) *Applications:* Widely used in automotive components due to their lightweight nature and acoustic insulation properties.
c) *Economic Viability:* Biocomposites reduce production costs by replacing expensive synthetic fibers with renewable alternatives like sisal or jute.
d) *Environmental Impact:* Recycling techniques for bio-composites are evolving but remain a challenge due to material heterogeneity.
e) *Cost comparison:* Sisal fiber ($0.65/kg) vs. E-glass fiber ($2.00/kg).
f) *Density comparison:* Flax fiber (1.5 g/cm ^{3}) vs. E-glass fiber (2.5 g/cm ^{3}).
g) *Carbon footprint reduction:* Biofiber/PHBV (Poly (β-hydroxybutyrate-co-β-hydroxyvalerate)) composites have lower greenhouse gas emissions than glass fiber-reinforced plastics.

2.4. Challenges

a) *Material Complexity:* Heterogeneous composites are difficult to recycle.
b) *Energy Intensity:* Manufacturing processes like curing consume significant energy.
c) *Performance Trade-offs:* Natural fibers often have lower mechanical strength compared to synthetic counterparts.

2.5. Research Gap

a) Develop mono-material composites for easier recycling.
b) Improve mechanical performance of natural fibers through surface modifications.
c) Scale up production of bio-based thermosets for broader industrial applications.
d) Foster global collaborations for standardizing sustainable practices.

3. Development

Materials used in biodegradable composites include:

1) Biopolymers
   a) Polylactic Acid (PLA): A widely used biodegradable polymer derived from renewable resources like corn starch.
   b) Polyhydroxyalkanoates (PHA): Produced by microbial fermentation, PHAs are known for their biodegradability and biocompatibility.
   c) Polycaprolactone (PCL): A biodegradable polyester that is flexible and has good mechanical properties.
2) Natural Fibers
   a) Jute: Known for its strength and biodegradability, commonly used as reinforcement.
   b) Flax: Offers mechanical properties similar to synthetic fibers and is lightweight.
   c) Hemp: Contains high cellulose content, providing excellent mechanical strength and moisture resistance.
   d) Kenaf: Used for its low density and good specific properties, making it suitable for various applications.
   e) Sisal: A hard fiber that enhances the toughness of composites while being environmentally friendly.
   f) Pineapple Leaf Fiber (PALF): A waste product with high cellulose content, offering superior mechanical properties.
3) Other Materials
   a) Wood Flour: Often used as filler in biodegradable composites to improve mechanical properties.
   b) Bamboo Powder: Reinforces biodegradable polymers like PCL, enhancing their performance.

These materials contribute to the development of sustainable composites that reduce environmental impact while maintaining desirable physical properties.

4. Innovation

To make composite manufacturing more sustainable, companies are focusing on efficient practices. This includes optimizing material use and processes to reduce waste, and using energy-efficient techniques like hot press molding for natural composites. Additionally, recycling composite components extends their lifecycle and reduces waste. Innovations like self - reinforced polymer composites (SRPs) make recycling easier by using a single material type. Recent innovations in biodegradable composites are making significant strides in sustainability and environmental impact.

1) IIT Delhi has developed biodegradable polymer composites specifically designed for biogas digesters. These materials can withstand harsh acidic conditions while ensuring that the digesters do not become long-term pollutants, thereby enhancing the longevity and performance of renewable energy systems.
2) Researchers in Germany are working on biodegradable polymers for encapsulating photovoltaic (PV) cells. These new materials aim to protect solar cells from environmental factors while being environmentally friendly themselves, thus reducing long-term waste associated with traditional encapsulants.
3) The University of Cambridge is developing biodegradable polymer composites for wind turbine blades, which traditionally use non-recyclable materials. These new blades are designed to match the strength and durability of conventional materials while being fully recyclable and biodegradable.
4) At the University of Illinois, researchers are creating high-performance biodegradable polymer composites for use in energy storage devices like batteries and supercapacitors. These innovations aim to replace traditional non-degradable components, thereby reducing the overall environmental footprint.
5) There is a growing focus on natural fiber composites (NFCs) made from materials like hemp and flax, which are combined with bio-based resins. These composites offer good mechanical properties along with biodegradability, making them suitable for various applications across industries, including automotive and construction.
6) Innovations in nanotechnology are enhancing the properties of biodegradable composites by incorporating nanoparticles to improve mechanical and thermal characteristics. This approach aims to create more robust and versatile materials suitable for demanding applications.
7) Recent advancements focus on "green composites" derived from renewable resources, such as agricultural waste. These materials not only reduce reliance on fossil fuels but also have a lower environmental impact compared to traditional composites.

These innovations in biodegradable composites highlight a significant shift towards sustainable materials that can help mitigate plastic pollution while meeting the performance requirements of various industries.

4.1. Innovative Application

With continued innovation, policy support, and global collaboration, biodegradable composites can become a cornerstone of sustainable industrial practices - helping industries reduce their environmental impact while advancing toward a circular economy.

Example: Flax Fiber Reinforced Composites in Automotive Door Panels (e.g., Mercedes-Benz)

a) Weight Reduction: \~25% compared to glass fiber-reinforced panels.
b) Fuel Efficiency Improvement: 0.5–0.9 L/100 km due to reduced vehicle weight.
c) End-of-Life Advantage: Full biodegradability or recyclability via low-temperature pyrolysis.

Benefit: Improved fuel economy, reduced emissions, and easier recycling make these composites particularly aligned with circular economy principles in mobility sectors.

4.2. Technological Advancements and Limitations

Recent progress in green manufacturing, fiber-matrix compatibility, and vitrimeric resin systems has significantly enhanced the performance of NFCs. Techniques such as Surface treatment (e.g., silane or alkaline), Resin transfer molding (RTM), 3D printing of bio-composites have improved adhesion, scalability, and dimensional accuracy.

Limitations

a) Hydrophilicity of natural fibers, affecting long-term durability.
b) Heterogeneity of constituents, complicating recycling.
c) Limited thermal resistance, which restricts high-temperature applications.
d) Higher moisture absorption, impacting mechanical stability.

4.3. Circular Economy and Sustainable Design Approaches

Sustainable composite design is increasingly aligned with Circular Economy principles:

a) *Eco-Design:* Prioritizes end-of-life recyclability and low-impact sourcing.
b) *Closed-loop Recycling:* Targets chemical and thermal recyclability of polymer matrices.
c) *Low-Carbon Feedstocks:* Utilizes agricultural residues and microbial-derived polymers.

Such systems aim to minimize waste, promote material reuse, and lower lifecycle emissions.

4.4. Challenges with Recycling Heterogeneous Composite Materials

While renewable composites offer environmental benefits, heterogeneity of matrix and reinforcement materials poses serious recycling challenges:

a) *Material Separation Complexity:* Thermoset matrices often form irreversible bonds with fibers.
b) *Degradation of Fibers During Recycling:* Mechanical and thermal recycling can damage fiber morphology and reduce mechanical properties.
c) *Lack of Standardized Recycling Infrastructure:* Unlike metals or plastics, composite recycling is fragmented and underdeveloped.
d) *Downcycling Risk:* Recycled material often has inferior properties, limiting high-performance reuse.

4.5. Life Cycle of Composite Materials

The life cycle of renewable composites emphasizes sustainability at every stage - from raw material extraction to end-of-life disposal. While advancements in recycling technologies and manufacturing processes have improved the environmental footprint of composites, challenges remain in durability and large-scale adoption.

a) Develop cost-effective recycling methods that maintain material quality.
b) Enhance the mechanical properties of natural fiber composites to match synthetic alternatives.
c) Standardize global practices for sustainable composite production and disposal.

Raw Material Extraction
↓
Processing
↓
Manufacturing
↓
Application
↓
End-of-Life Recycling/Disposal

Figure 1. *Life cycle of composite materials.*

Life Cycle Stages of Renewable Composites

1) Raw Material Extraction

a) This stage involves obtaining the raw materials needed to create composites, such as natural fibers (e.g., flax, hemp) or synthetic alternatives.
b) For bio-based composites, agricultural crops are grown, harvested, and transported for further processing.
c) Challenges include environmental impacts like land use, fertilizer runoff, and emissions from machinery during farming and extraction processes.

2) Processing

a) The extracted raw materials are processed into usable forms. For natural fibers, this includes cleaning, drying, and treating them to improve compatibility with polymer matrices.
b) Biodegradable matrices are often derived from agricultural by-products or bio-feedstocks like sugarcane ethanol.
c) Advanced technologies like thermal recycling can recover fibers from waste composites for reuse.

3) Manufacturing

a) Composites are manufactured by combining fibers with a matrix material (e.g., epoxy resin). Techniques include compression molding or injection molding.
b) Innovations in manufacturing focus on reducing energy consumption and waste while maintaining high-quality performance. For instance, hot press molding is used for natural fiber composites to optimize energy efficiency.

4) Application

a) Composites are used in various industries like automotive (lightweight parts), aerospace (structural components), and construction (panels).
b) Green composites are particularly valued for their lightweight nature, which improves fuel efficiency in vehicles and reduces overall emissions.
c) However, durability issues such as biodegradation and UV (ultra violet) exposure can limit their long-term applications.

5) End-of-Life Recycling/Disposal

a) At the end of their lifecycle, composites must be recycled or disposed of sustainably to minimize environmental harm.
b) Recycling methods include:
   i) Thermal Recycling: Recovering fibers through controlled incineration.
   ii) Upcycling/Downcycling: Reusing fibers for products of higher or lower quality.
   iii) Mechanical Recycling: Breaking down materials into smaller components for reuse.
c) Landfilling is discouraged due to strict regulations and environmental concerns.

Observations:

a) Recycling composite materials can recover up to 95–98% of carbon fibers and 80–82% of glass fibers using advanced thermal recycling methods.
b) Agricultural waste (e.g., pineapple leaves) is increasingly being used as reinforcement in bio-composites, reducing dependency on virgin materials.
c) Lightweight green composites improve fuel efficiency in vehicles but face durability challenges like moisture absorption and weathering effects.

4.6. Environmental Concerns in Raw Material Extraction

While biodegradable composites are superior to synthetic counterparts in many environmental metrics, attention must be given to raw material extraction:

a) Land use competition with food crops (e.g., corn for PLA).
b) Agrochemical runoff and associated eutrophication risks.
c) Energy demands for irrigation, harvesting, and fiber processing.
d) Transportation emissions, particularly for globally sourced feedstocks.

Sustainability metrics such as Water Footprint, Embodied Energy, and Global Warming Potential (GWP) must be holistically evaluated to ensure net environmental gains.

i. *Land Use Change:* Natural fiber crops (e.g., hemp, flax) may compete with food production.
ii. *Agrochemical Use:* Pesticides and fertilizers contribute to soil degradation and water pollution.
iii. *Energy Inputs:* Tractors, irrigation systems, and drying facilities consume fossil-based energy.
iv. *Carbon Emissions:* While lower than petrochemical feedstocks, farming and transportation still generate emissions (~0.1–0.3 kg CO_2/kg fiber).
v. *Sustainability Strategy:* Transition to low-impact crops (e.g., kenaf, hemp), adopt organic farming practices, and implement localized supply chains to reduce emissions.

5. Antimicrobial properties

Biodegradable polymers are increasingly being explored for their antimicrobial properties, making them valuable in biomedical and food packaging applications.

1) Intrinsic Antimicrobial Activity

a) Citrate-Based Polymers: Citric acid, a natural metabolite, is biocompatible and antimicrobial, giving citrate-based polymers unique advantages. Poly (octamethylene citrate) can suppress microbe proliferation by 70-80% due to its high citric acid content. These polymers can inhibit bacterial growth without needing antibiotics or silver nanoparticles, making them suitable for wound dressings and tissue engineering.
b) Chitosan: Chitosan, derived from chitin, has well-known bactericidal and bacteriostatic effects against a wide range of microorganisms.
c) Naturally Occurring Polymers: Extracellular matrix components exhibit antimicrobial activity.

2) Mechanisms of Action

a) Low pH (Power of Hydrogen): Organic acids like citric acid can lower pH, suppressing nicotinamide adenine dinucleotide (NADH) oxidation and leading to bacterial death.
b) Cell Wall Damage: Citric acid can alter the local pH or chelate metal ions in the cell wall, preventing nutrient absorption and causing cell death, especially in Gram-negative bacteria.
c) Cationic Polymers: Polymers with primary, secondary, or tertiary ammonium groups show high antimicrobial activity. Imidazolium-containing polymers have a low minimum inhibitory concentration (MIC) against bacteria and fungi.
d) Hydrophobic Groups: These groups can penetrate microbial membranes, causing cytoplasm leakage and cell death. Longer alkyl chains in antimicrobial cationic polymers enhance their effectiveness.
e) Main Chain Cationic Polymers: Multiple cationic centers in the polymeric backbone facilitate adsorption to microbial membrane surfaces.

3) Applications

a) Medical: Antimicrobial biomaterials can deliver therapeutic agents and provide prolonged antibacterial effects at the infection site, reducing systemic side effects. Examples include wound-healing biomaterials and implantable hydrogels.
b) Food Packaging: Antibacterial polymers can improve food safety and extend shelf life. Biodegradable materials that are non-toxic and cheap to produce are in demand for food wrapping.

4) Effectiveness Against Bacteria

a) Citrate-based polymers have demonstrated bacteria reduction against *Staphylococcus aureus and Escherichia coli.*
b) Chitosan is effective against Gram-positive bacteria.
c) Imidazolium-containing polymers show antimicrobial properties against most pathogenic bacteria.
d) Ternary blends based on biodegradable polymers have good antimicrobial properties against E. coli.

5) Considerations

a) The composition of cationic polymers determines their hemolytic activity, which corresponds to their bactericidal activity.
b) The type and length of hydrophobic alkyl chains affect the antimicrobial activity of polymers.

In summary, biodegradable polymers, especially those incorporating citric acid or chitosan, show promising antimicrobial properties. These materials have significant potential in medical and food packaging applications, offering solutions for preventing infections, improving food safety, and extending product shelf life.

6. Ocean Waste

Biodegradable polymers play a crucial role in reducing plastic waste in oceans by offering sustainable alternatives to traditional plastics.

i. Biodegradable polymers are designed to break down into harmless components when exposed to marine conditions. For instance, researchers at Osaka University have developed a plant-based plastic made from starch and cellulose nanofibers that degrades in seawater, significantly reducing the longevity of plastic waste in ocean environments. This innovation aims to mitigate the millions of tons of plastic waste that enter oceans annually.

ii. Unlike conventional plastics, which can persist for hundreds of years and release toxic substances as they degrade, biodegradable polymers can decompose into non-toxic byproducts. This characteristic is particularly important for marine ecosystems, where traditional plastics can cause harm to wildlife and leach harmful chemicals into the water.

iii. A team from the University of Rochester is creating bioplastics based on polyhydroxybutyrate (PHB), a biopolymer naturally produced by bacteria. These materials are engineered to degrade specifically in ocean environments, providing a solution for disposable oceanographic instruments that contribute to marine litter. The ability of these bioplastics to break down in the ocean is a significant advancement over existing biodegradable plastics, which often require industrial composting facilities.

iv. Many biodegradable polymers are produced from renewable resources, such as agricultural residues or waste materials. For example, researchers at NC State have developed a biodegradable material from leftover sawdust and agro-residues that not only reduces plastic pollution but also promotes zero-waste production processes. This approach minimizes the environmental footprint associated with plastic manufacturing.

v. Plastic pollution disproportionately affects marginalized communities, particularly in coastal areas with inadequate waste management systems. Biodegradable polymers can help alleviate this issue by reducing the volume of plastic waste that accumulates in these regions, thus contributing to environmental justice.

vi. The versatility of biodegradable polymers allows them to be used in various applications, including food packaging and single-use items like straws and bags, which are often found in ocean debris. The development of materials that can replace conventional plastics in these applications is vital for reducing overall plastic waste entering marine environments.

In summary, biodegradable polymers offer promising solutions to combat ocean plastic pollution by decomposing safely in marine environments, reducing harmful residues, and promoting sustainable production practices. Their development is essential for creating a circular economy that minimizes environmental impact while addressing the urgent challenge of plastic waste in our oceans.

7. Benefits, Limitations, and Examples

Biodegradable polymers can significantly impact the shelf life of food products, offering both benefits and challenges.

Benefits

i. Extended Shelf Life: Certain biodegradable polymers can extend the shelf life of perishable goods due to their antimicrobial properties. For example, a biodegradable polymer made from oat starch has been shown to double the shelf life of certain perishable goods.

ii. Modified Atmosphere Packaging (MAP): Polymers can be used to create a controlled atmosphere inside packaging, which adjusts the gas composition to extend the shelf life of fresh produce, bakery items, and processed meats.

iii. Edible Coatings: Some biodegradable polymers can be applied as edible coatings directly on food, which can prolong the shelf life of fresh fruits.

iv. Active Packaging: Bio-based biodegradable polymers are used in active packaging to preserve the authentic qualities of food, surpassing the roles of conventional passive packaging. This helps in providing healthier and safer foods with extended shelf life.

v. Reduces Food Waste: By preserving food for longer periods, polymers in food packaging contribute to the reduction of food waste.

vi. Comparable or Longer Shelf Life: Biodegradable films have been shown to guarantee the same or even a longer shelf life than that provided by conventional polymer films. This was found to be the case for apple salad and minimally processed shredded carrots stored at 4 ℃.

Considerations and Limitations

Composite materials face several challenges in achieving sustainability. Material Complexity is a significant issue because heterogeneous composites, which combine different materials, are hard to recycle. This requires advancements in how materials are designed and processed. Another challenge is Energy Intensity; manufacturing processes like curing and consolidation consume a lot of energy, which contributes to environmental problems. Additionally, there is Performance Trade-offs. Natural composites often have weaker mechanical properties compared to synthetic ones, so more research is needed to improve their performance without sacrificing sustainability.

i. Barrier Properties: Bio-based biodegradable polymers may be more susceptible to water than fossil-based polymers and often have poor mechanical and barrier properties.

ii. Thermal Resistance: The thermal resistance of biodegradable polymers can be inadequate, depending on the specific type of biopolymer.

iii. Cost and Consumer Acceptance: The market success of active packaging depends on consumer acceptance, who weigh the benefits, such as fresher, safer food with a longer shelf life, against potential risks, including the higher cost of active packaging-treated food and safety concerns.

iv. Composting Requirements: Some biodegradable polymers, like PLA, require industrial composting for degradation.

Examples

i. Oat Starch Polymer: A biopolymer developed from oat starch can replace plastic packaging, conserve the taste and smell of packaged goods, and double the shelf life of certain perishable goods.

ii. Starch: Starch is a versatile natural biopolymer for bio-thermoplastic food packaging due to its availability, good film-forming ability, renewability, biodegradability, excellent barrier quality, safety, and economical attributes.

iii. Zein: Zein, a byproduct of the starch industry, has great potential for use in sustainable food packaging due to its adhesive film-forming potential, good barrier properties, high thermal resistance, biodegradability, antimicrobial and antioxidant activity, and cost-effectiveness.

iv. PLA: PLA has gained attention in packaging due to its chemical resistance, excellent transparency, and effective flavor and odor barrier.

Overall, biodegradable polymers offer promising solutions for extending the shelf life of food products, reducing food waste, and promoting sustainability in the food industry. However, it's important to carefully consider their limitations and choose the appropriate polymer based on the specific application and requirements.

8. Future Research and Development

Biodegradable composites present a promising and eco-friendly alternative to conventional materials, with the potential to significantly reduce environmental impact across various industries. Future applications include natural fiber-based automotive parts, biopolymer blends with improved strength, wind turbine blades, energy storage systems, and 3D-printed products made from bio-based materials. However, their widespread use faces challenges such as limited scalability, high production costs, weaker mechanical performance, lack of standard testing and certification, and inadequate recycling infrastructure. To overcome these barriers, research and development efforts are focused on industrial-scale manufacturing, enhancing material properties, and establishing circular economy systems like urban biorefineries. Strategic directions include developing hybrid composites with self-healing or reversible matrices, standardizing quality and testing protocols, integrating eco-design practices, and increasing government support through funding and incentives. With ongoing innovation and global cooperation, biodegradable composites can become a key sustainable material for the future.

9. Conclusion

The growing environmental crises - such as plastic pollution, climate change, and resource depletion - highlight the urgent need for sustainable material alternatives. This paper examines biodegradable and renewable composites made from natural fibers and bio-based polymers as eco-friendly substitutes for conventional plastics. These materials are gaining traction in sectors like packaging, automotive, and healthcare due to their biodegradability, low carbon footprint, and compatibility with green manufacturing. While promising, challenges remain in scaling production, improving long-term performance, and establishing standard recycling protocols. Advancing biodegradable composites will require innovation, collaboration, and strong policy support to ensure they contribute effectively to a circular and sustainable economy.

Abbreviations

PHA	PolyhydroxyAlkanoates
PLA	PolyLactic Acid
PBS	Polybutylene Succinate
PCL	PolyCaproLactone
NFC	Natural Fiber Composites
LDPE	Low Density PolyEthylene
HDPE	High Density PolyEthylene
PET	PolyEthylene Terephthalate
PP	PolyPropylene
PMMA	PolyMethyl MethAcrylate
PVC	Poly Vinyl Chloride
PPSU	PolyPhenylSulfone
PC	PolyCarbonate
ABS	Acrylonitrile Butadiene Styrene
DDM	4,4’-Diaminodiphenylmethane
LCA	Life Cycle Assessment
PHBV	Poly (β-hydroxybutyrate-co-β-hydroxyvalerate)
PALF	Pineapple Leaf Fiber
SRP	Self Reinforced Polymer
PV	PhotoVoltaic
RTM	Resin Transfer Molding
UV	Ultra Violet
GWP	Global Warming Potential
NADH	Nicotinamide Adenine Dinucleotide
MIC	Minimum Inhibitory Concentration
PHB	PolyHydroxyButyrate
PH	Power of Hydrogen
MAP	Modified Atmosphere Packaging

Conflicts of Interest

The authors declare no conflicts of interest.

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