International Research Journal of Biological Sciences ISSN 2278-3202
Vol. **15(4),** 40-44, November **(2026)** *Int. Res. J. Biological Sci.*

Review Paper

Bioplastics: A Sustainable Alternative for the Circular Economy

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Available online at: www.isca.in, www.isca.me
Received 6th August 2026, revised 10th September 2026, accepted 15th October 2026

Abstract

Persistent plastic residues now constitute a major environmental burden because most conventional polymers remain in ecosystems long after disposal. Petroleum-based plastics have become integral to contemporary life owing to their low price, durability and broad functional range, yet these same characteristics contribute to long-term terrestrial and marine contamination, greenhouse-gas emissions and microplastic generation. Bioplastics provide an alternative materials platform in which renewable biological feedstocks can replace part or all of the fossil-derived carbon, while selected polymer classes can also undergo biodegradation under defined conditions. Their use now extends across packaging, agriculture, healthcare, textiles and electronic applications. Nevertheless, higher production costs, scale-up constraints, variable material performance and inadequate end-of-life infrastructure continue to limit broad deployment. This review examines the major classes and production routes of bioplastics, compares them with conventional polymers, and considers their applications, environmental relevance, current limitations and future role in circular material systems.

Keywords: Bioplastics, biodegradation, sustainability, renewable resources, circular economy, polymer science.

Introduction

Synthetic polymers reshaped twentieth-century manufacturing because inexpensive, lightweight and durable materials could be adapted to an exceptionally wide range of products. The same resistance to physical and chemical deterioration that makes conventional plastics useful, however, also permits discarded material to remain in the environment for very long periods. As plastic production and consumption have expanded, residues have accumulated in both land and aquatic systems, with consequences for ecological integrity and biodiversity. Petroleum-derived polymers may persist for centuries after disposal[1]. Fragmentation of larger plastic items additionally generates microplastics that can move through food webs and enter biological systems, creating a growing environmental and public-health concern[2].

These pressures have stimulated interest in materials that reduce reliance on fossil carbon and are more compatible with circular resource use. Bioplastics form an important part of this transition. Depending on polymer chemistry and feedstock, they may incorporate renewable carbon, offer defined biodegradation pathways, or combine both attributes. Their value therefore lies not in a single universal property but in the possibility of designing material systems with a lower dependence on finite fossil resources and more appropriate end-of-life options[3].

Principal Differences between Conventional Plastics and Bioplastics

The distinction between conventional plastics and bioplastics begins with feedstock origin but extends to manufacturing, degradation behaviour, environmental burden and end-of-life management (Table-1).

Most established plastics are manufactured from crude-oil or natural-gas fractions. Polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC), for example, are produced through mature petrochemical routes. Their manufacture is embedded in fossil-resource supply chains and contributes to resource depletion, energy demand and greenhouse-gas emissions[4].

Bioplastics, by contrast, may obtain some or all of their carbon from renewable biomass, including starch, cellulose, vegetable oils, sugarcane, corn and products of microbial fermentation. Important examples are polylactic acid (PLA), polyhydroxyalkanoates (PHAs), thermoplastic starch and bio-based polyethylene. Biological origin should not be treated as synonymous with biodegradability: a bio-based polymer may remain non-biodegradable, while certain fossil-derived polymers can be designed to biodegrade. Consequently, environmental performance must be assessed from polymer chemistry and life-cycle conditions rather than feedstock origin alone[5]. The environmental burden of conventional polymers is strongly associated with fossil-carbon use, persistent litter and the progressive formation of microplastic particles. Because many common petrochemical plastics degrade only very slowly, they can accumulate in ecosystems and contribute to exposure through food chains[6].

Renewable feedstocks may lower the fossil-carbon component of bioplastic production, and plant biomass can incorporate atmospheric carbon during growth. These potential benefits are nevertheless conditional: agricultural practice, land-use change, processing energy and disposal routes all influence the final life-cycle balance[7].

Degradation behaviour is similarly context dependent. The stable carbon frameworks of many conventional polymers resist microbial breakdown. Selected biodegradable materials, including PHA, PLA and several starch-based systems, can instead be metabolized or decomposed under appropriate conditions. Effective degradation is not automatic in the open environment, however; some materials require controlled industrial composting with defined temperature, moisture and microbial activity[1].

Conventional plastics retain a dominant position in packaging, construction, vehicles, medical products, textiles and consumer goods because established manufacturing delivers reliable mechanical performance at low cost. Bioplastics are increasingly used where renewable sourcing, biodegradation or biocompatibility provides an additional functional advantage, including food packaging, agricultural films, disposable products, drug-delivery systems and tissue-engineering scaffolds[8].

Their contribution to a circular economy therefore depends on matching the polymer to its intended use and disposal pathway rather than assuming that one material class can replace all conventional plastics[9]. Table-1 illustrates the principal differences between conventional plastics and bioplastics with respect to their source materials, environmental impact, biodegradability, applications, and sustainability characteristics.

Classification of Bioplastics

Bioplastics can be organized according to two independent criteria: the origin of their carbon feedstock and their capacity for biological degradation. This distinction avoids the common misconception that every bio-based material is necessarily biodegradable.

Bio-based, non-biodegradable plastics: In this group, renewable biological resources provide the feedstock, but the resulting polymers retain durability and physicochemical behaviour comparable with conventional plastics[10]. Bio-polyethylene (Bio-PE), bio-polyethylene terephthalate (Bio-PET) and bio-polyamide (Bio-PA) are representative examples.

Table-1: Comparative characteristics of conventional plastics and bioplastics.

Parameter	Conventional plastics	Bioplastics
Primary raw materials	Petroleum and natural gas	Corn starch, sugarcane, cellulose, algae, vegetable oils, and microbial biomass
Source of carbon	Fossil fuels	Renewable biological resources
Biodegradability	Generally non-biodegradable	Completely or partially biodegradable, depending on the polymer
Carbon footprint	Relatively high	Comparatively lower
Environmental impact	Long-term environmental persistence and microplastic accumulation	Reduced environmental burden and improved sustainability
Energy consumption	High dependence on fossil fuels	Reduced dependence on non-renewable resources
Mechanical strength	Usually high	Variable according to composition and manufacturing process
Thermal stability	Generally high	Moderate to high, depending on the material
Production cost	Lower owing to large-scale production	Relatively higher because of technological and infrastructural limitations
Recycling and disposal	Mechanical recycling, incineration, and landfilling	Composting, biodegradation, recycling, and anaerobic digestion
Major applications	Packaging, construction, electronics, and automobiles	Packaging, agriculture, medicine, textiles, and electronics
Examples	Polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS)	Polylactic acid (PLA), polyhydroxyalkanoates (PHAs), thermoplastic starch (TPS), and polybutylene succinate (PBS)
Contribution to the circular economy	Limited	Significant

Bio-based, biodegradable plastics: These polymers combine renewable feedstock origin with the ability to undergo biologically mediated breakdown when suitable environmental or processing conditions are provided[11]. PLA, PHAs and thermoplastic starch (TPS) are prominent members of this category.

Fossil fuel-derived biodegradable plastics: Biodegradability is not restricted to polymers made from biomass. Certain materials synthesized from petrochemical precursors possess chemical structures that permit biological degradation[12]. Polybutylene succinate (PBS) and polycaprolactone (PCL) illustrate this category.

Sources and Production Methods

Starch-based bioplastics: Starch from maize, cassava, potato and wheat is widely used as a renewable polymer feedstock. Through plasticization and mechanical processing, native starch can be converted into thermoplastic formulations that are suitable for industrial manufacture and blending with other polymers[10].

Cellulose-based bioplastics: Cellulose, an abundant structural biopolymer in plants, provides another major renewable resource. Chemical derivatization of cellulose enables materials such as cellulose acetate and related products to be manufactured with properties suitable for commercial applications[3].

Microbial bioplastics: Some microorganisms accumulate polyhydroxyalkanoates intracellularly, particularly when carbon is available but other nutrients become limiting. These microbial polyesters are notable for their biocompatibility and capacity for biodegradation[1]. Production of polyhydroxybutyrate (PHB) has also been demonstrated using marine Vibrio strains, illustrating the diversity of microbial platforms that may be exploited for polymer biosynthesis[13].

Algal bioplastics: Marine algae are being investigated as feedstocks because they grow rapidly, do not require conventional agricultural land to the same extent as food crops, and may reduce freshwater demand. These features make algal biomass relevant to efforts to diversify renewable inputs for future bioplastic production.

Applications of Bioplastics

Packaging industry: Packaging currently represents a major commercial outlet for bioplastic materials. Products include food-contact films and containers, shopping bags, disposable service ware and other short-life items for which end-of-life design is particularly important. Renewable food-packaging systems and approaches for improving barrier performance have also been reviewed in the ISCA Research Journal of Chemical Sciences[14].

Agricultural applications: Agricultural uses include biodegradable mulch films, seed coatings, irrigation-related components and matrices for controlled nutrient release. In these settings, material selection can potentially reduce the need to retrieve persistent plastic residues after use.

Biomedical applications: The combination of biocompatibility, processability and controllable degradation has enabled PLA, PHAs and related polymers to be used in sutures, tissue-engineering constructs, drug-delivery systems, wound-care materials and selected prosthetic or implantable devices[12]. A 2026 ISCA review likewise describes biodegradable plastics in drug delivery, tissue-engineering scaffolds and implantable biomedical technologies[15].

Textile and electronics industries: Research is also extending toward biodegradable fibres and more sustainable polymeric components for electronic products. These applications require materials that can satisfy performance requirements while reducing dependence on persistent fossil-derived plastics.

Environmental Significance

The sustainability relevance of bioplastics is broader than the diversion of visible plastic waste. Substitution of renewable carbon for fossil feedstocks can reduce dependence on non-renewable resources, while selected production systems may also lower greenhouse-gas emissions[11].

When material design is linked to recycling, composting or other appropriate recovery routes, bioplastics can contribute to circular resource management. Potential benefits include lower fossil-resource consumption, reduced persistence of selected waste streams, diminished long-term microplastic generation and support for more resource-efficient industrial systems. These advantages are not intrinsic to every bioplastic product and must be evaluated across the complete life cycle.

Challenges and Limitations of Bioplastics

Expansion of the bioplastics sector is constrained by a combination of economic, technical, environmental and infrastructural factors. Renewable sourcing and potential biodegradability do not by themselves guarantee that a material will be cost competitive or environmentally preferable. Wider adoption therefore depends on improvements in manufacturing efficiency, responsible feedstock selection, reliable performance, clear standards and end-of-life systems that are compatible with each polymer type.

Economic Limitations: Production costs remain a major obstacle to commercial expansion. Many bioplastic processes operate at a smaller scale than mature petrochemical manufacturing and require comparatively expensive biomass preparation, fermentation, polymer recovery or purification.

Conventional plastics, in contrast, benefit from decades of process optimization, extensive infrastructure and economies of scale. As a result, many bio-based alternatives still face a cost disadvantage[10]. Feedstock-price variability, energy requirements and investment in specialized equipment add further uncertainty. Advances in fermentation, enzymatic conversion and polymer synthesis may progressively narrow this gap, but cost parity has not yet been achieved across the sector[10].

Competition for Natural Resources: First-generation bio-based plastics may rely on corn, sugarcane, wheat, cassava and other agricultural crops that also have food or feed value. Large-scale diversion of such resources to polymer manufacture can increase pressure on cultivable land, irrigation water and fertilizer inputs and may create indirect effects on biodiversity and food systems. Sustainable expansion therefore requires careful attention to land use and regional resource constraints. Current research increasingly emphasizes non-food feedstocks such as agricultural residues, lignocellulosic biomass, algae and organic waste so that polymer production can be decoupled from direct competition with food crops[3].

Technical Limitations: Performance requirements also restrict substitution in demanding applications. Some biodegradable polymers have lower heat resistance, impact strength, flexibility or service life than established materials such as PET, PP and high-density polyethylene. PLA illustrates this trade-off: it offers transparency and can biodegrade under industrial composting conditions, but brittleness, limited thermal tolerance and weak impact resistance constrain use in high-temperature or long-duration structural settings. Blending, reinforcement and chemical modification can improve performance, although these interventions may in turn alter recyclability or degradation behaviour[3].

Waste Management Infrastructure: Appropriate disposal infrastructure is essential if the designed environmental advantages of biodegradable plastics are to be realized. Many products require industrial composting conditions rather than uncontrolled exposure in soil or water. Such facilities remain unevenly distributed, particularly in lower-resource settings. In addition, unclear labels and limited consumer understanding can lead biodegradable items to enter conventional recycling streams, where they may interfere with material sorting and reprocessing. Effective systems therefore require standardized identification, separate collection where necessary, adequate composting or recycling capacity, public education and harmonized regulatory guidance. Without these end-of-life arrangements, bioplastics may reproduce some of the waste-management problems associated with conventional materials[9].

Future Perspectives

Next-generation bioplastics are increasingly being shaped by synthetic biology, metabolic engineering, nanotechnology and computational approaches. Microbial production hosts can be redesigned to channel carbon more efficiently toward polymer synthesis, while metabolic engineering can improve yield, alter monomer composition and broaden the range of usable renewable substrates[12]. Such strategies may help address two persistent barriers: production cost and industrial scalability.

Research is also shifting toward agricultural residues, lignocellulosic biomass, food-processing by-products, organic waste and marine algae. These resources can reduce direct reliance on edible crops while integrating polymer production with circular-bioeconomy concepts. At the materials level, nanocomposite strategies offer routes to strengthen mechanical, thermal and barrier properties, potentially extending bioplastics into more demanding packaging, biomedical and agricultural applications.

Artificial intelligence and machine-learning methods may further support materials development by relating formulation and process variables to polymer performance, optimizing manufacturing conditions and screening candidate materials for defined functions. Translation to industrial practice will nevertheless depend on collaboration among biotechnology, materials science, engineering, industry, regulatory bodies and environmental agencies. Future progress must therefore integrate polymer innovation with scalable production, credible life-cycle assessment, coherent regulation and practical end-of-life infrastructure.

Conclusion

Bioplastics provide a diversified materials strategy for reducing dependence on conventional fossil-derived polymers rather than a single universal solution to plastic pollution. Their principal opportunities arise from renewable feedstocks, tailored degradation behaviour and adaptability across packaging, agriculture, biomedical and other applications. At the same time, cost, material-performance constraints, resource competition and inadequate disposal infrastructure can substantially modify their environmental value. Continued advances in biotechnology, materials engineering and circular waste systems are likely to improve their feasibility. The long-term contribution of bioplastics will ultimately depend on selecting appropriate polymers for specific applications and coupling production with responsible sourcing and effective end-of-life management.

Acknowledgements

The author gratefully acknowledges the contributions of Dr. Vibha Ahuja, Senior Advisor, South Asia Biosafety Program (SABP) and Technical Advisor, Biotech Consortium India Limited (BCIL). I would like to extend my heartfelt gratitude to Dr. Archana Majumdar, a Member of the National Commission for Women and an Independent Director at Moil Limited, Ministry of Steel, Government of India.

Funding: This work received private, non-institutional research support from the Sri Sarosij Ray and Smt Nandarani Ray Research Support Fund, a family-supported fund established in honour of Sri Sarosij Ray and Smt Nandarani Ray in recognition of their contributions to society. The fund is not affiliated with any governmental, academic, commercial, or public funding agency.

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