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Review Article

From pond to polymer: A concise review on algae-derived plastics

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Abstract. Algae-derived plastics signify a revolutionary advancement in the pursuit of sustainable materials, providing a renewable and environmentally benign substitute for conventional petroleum-based polymers. This review explores the most recent advancements in algae cultivation, polymerization methodologies, and synthetic biology that have elevated algae-based bioplastics to a position of prominence. It emphasizes the distinctive characteristics of algal biopolymers, their capacity to sequester carbon, and their various applications, encompassing packaging and 3D printing. Nonetheless, the pathway from aquatic environments to polymeric substances is laden with obstacles, including elevated production costs, challenges related to scalability, and regulatory impediments. Through the analysis of case studies, market dynamics, and burgeoning research, this paper highlights the pivotal importance of algae-derived plastics in fulfilling circular economy objectives and mitigating plastic pollution. The review culminates with an appeal for international collaboration, policy advocacy, and sustained investment in algae bioplastics to realize their complete potential as a fundamental element of sustainable development.

Keywords: Algae-derived plastics, Sustainable bioplastics, Circular economy, Plastic pollution mitigation

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1. Introduction

Algae-derived plastics represent a significant advancement in the pursuit of sustainable materials, offering a promising alternative to conventional petroleum-based plastics (Cheah et al., 2023). The exploration of algae for bioplastics traces back to early biofuel research in the 20th century, with notable progress in the early 2000s, when advancements in algal biotechnology enabled the extraction of essential precursors such as carbohydrates, proteins, and lipids for polymer production (Tennakoon et al., 2023). Unlike conventional plastics, which are cost-effective and durable but contribute heavily to global pollution and greenhouse gas emissions, algae-based plastics are synthesized from renewable resources and often exhibit biodegradability (Phillip, 2024). Their unique advantages include fast growth rates, non-reliance on arable land, and the ability to thrive in saline or wastewater systems, setting them apart from other bio-resources like corn or sugarcane (Cheah et al., 2023). Algae's high photosynthetic efficiency, with certain species like Chlorella vulgaris and Spirulina platensis producing up to 40% of their dry weight in lipids or carbohydrates, underscores their potential as a sustainable feedstock for polymers like polylactic acid (PLA) (Aswathi Mohan et al., 2022). The environmental burden of conventional plastics is immense, with over 300 million tons produced annually and less than 10% recycled, leading to pollution and significant carbon emissions of approximately 1.8 gigatons annually (Phillip & Chauhan, 2024). Algae-based plastics align with circular economy principles, offering solutions such as complete biodegradability and integration with waste management practices, where algae utilize industrial CO_2 emissions to produce valuable biomass (Yap et al., 2023). The bioplastics industry, which grew from 2.11 million tons in 2019 to an estimated 2.87 million tons in 2023, highlights the growing adoption of sustainable alternatives driven by consumer demand and legislative actions like the EU's Single-Use Plastics Directive (Kiessling et al., 2023). Companies like Algix and Bloom have pioneered algae-derived plastics for diverse applications, ranging from footwear to packaging (Allnutt, 2019). Projections from European Bioplastics and the International Energy Agency estimate that bio-based polymers could constitute 40% of the global plastics market by 2040, positioning algae-derived plastics as a critical innovation in achieving environmental sustainability and addressing the challenges of plastic pollution (Dornburg et al., 2008).

2. Recent advancements in algae-based polymer technology

The field of algae-based polymer technology has made significant strides, marked by advancements in extraction methods, genetic engineering, and material processing techniques. Breakthroughs include the conversion of algal carbohydrates, such as

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starches and cellulose, into high-performance polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHA) (Kalita et al., 2021; Mal et al., 2022b). PLA, known for its biodegradability, is ideal for packaging and disposable goods, while PHA offers superior mechanical properties and biocompatibility, making it suitable for medical applications (Leong & Chang, 2022). Genetic engineering has further optimized algal strains, such as Chlamydomonas reinhardtii, to enhance starch production for more efficient PLA synthesis (Adetunji & Erasmus, 2024). Additionally, whole algae biomass is now being utilized in composite materials, resulting in reinforced bioplastics with greater strength and durability (Kong et al., 2023). The industry's growth is driven by pioneering companies like Algix and Bloom, which have developed algae-based solutions ranging from footwear soles to biodegradable sports equipment, often in collaboration with academic institutions such as the University of California, San Diego (Malkar et al., 2023). These efforts are supported by substantial public and private sector investments, including the U.S. Department of Energy's $15 million allocation in 2023 and over $500 million in venture capital funding for algae-derived plastics research (Behera et al., 2022). The global algae-derived plastics market, valued at $280 million in 2022, is projected to grow at a compound annual growth rate (CAGR) of 6.8% through 2030, underscoring increasing consumer demand and the sector's potential to become a mainstream alternative to traditional polymers (Tennakoon et al., 2023). This confluence of technological innovation, industry collaboration, and financial backing highlights the transformative potential of algae-derived plastics in fostering sustainability and reducing environmental impact.

3. Various uses of algae-derived plastics in different sectors

Algae-derived plastics have emerged as a versatile and eco-friendly alternative to conventional polymers, finding applications across various industries due to their biodegradability and comparable performance. In the packaging sector, algae-based materials such as polyhydroxyalkanoates (PHA) are being utilized as sustainable replacements for single-use plastics like bags and food containers, addressing critical waste issues while maintaining durability (Yap et al., 2023). In textiles, these biopolymers are blended with natural fibers to produce breathable, moisture-resistant fabrics that appeal to eco-conscious consumers (Abdulkadhim & Habeeb, 2022). The biomedical industry is leveraging the biocompatibility of algae-derived polymers such as alginate for biodegradable sutures, wound dressings, and advanced drug delivery systems, with alginate-based hydrogels playing a key role in tissue engineering (Mirzaei et al., 2023). Additionally, the automotive sector incorporates lightweight and durable algae-based plastics in interior components, enhancing fuel efficiency and reducing emissions (Sharma et al., 2023). Notable applications include Bloom's algae-based foam used in footwear, which not only replaces petroleum-derived materials but also utilizes algae biomass to combat water pollution (Mal et al., 2022a). Similarly, startups are producing compostable water bottles made from algae-based PLA as eco-friendly alternatives to conventional plastics (Coppola et al., 2021). The demand for sustainable packaging, projected to reach $341 billion by 2030, presents significant opportunities for algae-derived materials, supported by regulatory bans on single-use plastics (Wang et al., 2023). The biomedical bioplastics market, valued at $800 million in 2022, and the automotive industry's push for sustainable materials highlight the growing adoption of algae-based innovations (Fabris et al., 2020). With an anticipated compound annual growth rate (CAGR) of 7.2% through 2030, algae-derived plastics are poised to revolutionize material science, driving the global transition to sustainable practices while mitigating the environmental impact of traditional plastic uses (Araújo et al., 2021).

4. Environmental impact of using algae in plastic production

The integration of algae in plastic production offers profound environmental benefits over conventional petroleum-based plastics, notably in reducing greenhouse gas (GHG) emissions. Algae cultivation efficiently captures carbon dioxide through photosynthesis, with some species sequestering up to 2 kg of CO_2 per kilogram of dry biomass, significantly offsetting emissions from industrial processes (Malkar et al., 2023). Unlike terrestrial bioresources like corn or sugarcane, algae do not require arable land or freshwater, thereby avoiding competition with food crops and addressing concerns about land and water resource use. With their rapid growth rates and ability to thrive in saline or wastewater environments, algae present a highly sustainable alternative for producing bioplastics (Khyalia et al., 2022). Life cycle analysis (LCA) reveals the environmental advantages of algae-derived plastics across production, usage, and disposal stages. For instance, while photobioreactors used for algae cultivation are energy-intensive, advancements like solar-powered systems are lowering their energy demands (Mahmood et al., 2023). Polymer extraction methods, such as those used for producing polylactic acid (PLA) and polyhydroxyalkanoates (PHA), have been optimized to enhance energy efficiency, and these bioplastics show superior biodegradability compared to petroleum-based counterparts, (Anto et al., 2020). Algae-based PLA, degrades in 6–12 months under composting conditions, far outpacing the centuries-long persistence of traditional plastics (Chamas et al., 2020). According to (Abdul-Latif et al., 2020), analysis highlighted that algae-based plastics emit only 1.5–2.0 tons of CO_2 per ton of polymer, compared to 4–6 tons for conventional plastics. Furthermore, coupling algae cultivation with wastewater treatment enhances sustainability by recycling nutrients and reducing overall environmental impact (Srimongkol et al., 2022). As global regulations tighten and consumer demand for sustainable products, algae-derived plastics are poised for widespread adoption, supported by their reduced carbon footprint, biodegradability, and compatibility with renewable energy innovations, potentially reshaping the global plastics industry and significantly reducing its ecological footprint.

5. Challenges in the widespread adoption of algae-derived plastics

The adoption of algae-derived plastics faces significant technical, economic, and regulatory challenges despite their promising potential. High production costs remain a major hurdle, with photobioreactors being capital-intensive and energy-intensive, while harvesting and polymerization processes contribute an additional 20–30% to overall expenses (Penloglou et al., 2024). These cost barriers are compounded by scalability issues, as most algae-based plastics are produced at laboratory or pilot scales rather than industrial levels. Companies like Algix have demonstrated niche successes, but limited production capacities fail to meet the vast global demand for conventional plastics (Little, 2014). Maintaining algal monocultures to ensure consistent yields is another challenge due to contamination risks, while innovations in genetic engineering and bioprocess optimization remain costly and complex to implement (Luo et al., 2020). Regulatory hurdles, such as the lack of standardized definitions and certifications for biodegradable plastics, further complicate market acceptance. Consumer reluctance to pay premium prices for algae-derived plastics, with a survey showing that 65% of consumers are unwilling to pay more than a 10% markup, limits their competitiveness against cheaper petroleum-based alternatives (Mehta et al., 2021). While countries like Germany and Japan offer incentives for sustainable materials, many regions lack adequate policy support, with the U.S. federal government allocating just $15 million to algae-based material research, an amount deemed insufficient by industry stakeholders (Zeng et al., 2022). The global market for biodegradable plastics, valued at $8 billion in 2022, saw algae-derived plastics contributing less than 5%, compared to the $600 billion market dominance of petroleum-based plastics (Jiao et al., 2024). Despite these barriers, successful case studies, such as Bloom's collaboration with footwear brands using subsidies and eco-conscious marketing, highlight the potential of algae-based plastics in targeted applications (Malkar et al., 2023). Addressing these challenges will require investments to lower production costs, the establishment of clear regulatory frameworks, and robust financial incentives to foster adoption. Without such measures, the widespread industrial use of algae-derived plastics will remain constrained despite their environmental advantages.

6. Future directions in algae-derived plastics

The future of algae-derived plastics depends on addressing existing limitations through focused research and innovative technologies. Cost-effective algae cultivation techniques, such as wastewater-based systems, offer dual benefits of nutrient recycling and reduced environmental impact, potentially cutting production costs by 40–50% (Liu & Hong, 2021). Advances in synthetic biology, including CRISPR-Cas9, have enhanced polymer yields, with recent studies reporting a 30% improvement in bioplastic precursors like PHA and PLA (Dhokane et al., 2023). Additionally, novel algae strains, such as red algae, exhibit superior material properties like increased thermal stability, expanding their applications in packaging and industrial uses (Kapoor et al., 2024). The integration of these bioplastics into emerging technologies, such as 3D printing, has demonstrated their potential in high-value areas like biodegradable medical implants, while circular design principles further promote recyclability and waste reduction across industries (Andanje et al., 2023). Projections from the IEA and UNEP underscore algae-derived plastics' significant role in decarbonizing the plastics sector, with estimates suggesting a 50% reduction in emissions by 2050 (Bin Abu Sofian et al., 2024). The global market for algae-based bioplastics, growing at a CAGR of 7.2%, is expected to reach $2.1 billion by 2030, driven by policy support and increasing demand for sustainable alternatives, particularly in regions like the EU and Japan (Biernat, 2022). With initiatives such as the EU's €50 million allocation for algae research and efforts in emerging markets like India and Brazil, algae-derived plastics are poised to play a transformative role in achieving global sustainability goals (dos Santos et al., 2023; Srinithi et al., 2023). By advancing genetic engineering, optimizing bioprocesses, and integrating these materials into cutting-edge applications, algae-based plastics can address environmental challenges and contribute significantly to a circular economy (Aswathi Mohan et al., 2022; Devadas et al., 2021; Olabi et al., 2023).

7. Conclusion

Algae-derived plastics present significant environmental advantages, such as reducing carbon emissions and mitigating plastic pollution, with innovations in algae cultivation techniques like wastewater-based systems and advances in synthetic biology improving production efficiency and cost-effectiveness. However, challenges persist, particularly in scaling production, managing cultivation costs, and establishing clear regulatory frameworks. Moreover, algae-based plastics face economic and market barriers, including higher production costs and consumer price sensitivity, which hinder their competitiveness against petroleum-based alternatives. Despite these hurdles, the unique properties and carbon-negative potential of algae position it as a transformative resource for sustainable polymer production. To fully realize its potential, investment in research and development is crucial, with further innovations needed in algae cultivation, genetic engineering, and polymer processing to reduce costs and improve scalability. Collaboration among industry stakeholders is essential to build efficient bioplastic production methods and integrate algae-based materials into mainstream manufacturing, while policymakers must establish supportive regulations and incentives to foster market growth. Global cooperation from both the public and private sectors is needed to tackle the environmental crisis caused by plastic pollution, and algae-based plastics offer a promising solution to reduce reliance on fossil fuels, minimize environmental harm, and contribute to a circular economy.

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