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GREEN GOLD: HARNESSING ALGAE'S POTENTIAL AS A SUSTAINABLE BIOPLASTIC SOURCE

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Abstract: Bioplastics have emerged as a promising alternative to conventional plastics due to their potential for reduced environmental impact and enhanced biodegradability. Among the various sources for bioplastic production, algae, a diverse group of photosynthetic organisms, have gained considerable attention as a sustainable and renewable feedstock. This review paper aims to provide a comprehensive overview of the current state of knowledge regarding algae as a viable source for bioplastic production. It explores the unique characteristics of algae, discusses the different types of bioplastics that can be derived from algae, and addresses the key challenges and opportunities associated with algae-based bioplastics. Additionally, this paper highlights recent advancements in bioplastic processing techniques and explores potential applications of algae-based bioplastics across various industries. Overall, the findings of this review underscore the significant potential of algae as eco-friendly and commercially viable alternative to conventional plastic materials.

Index Terms - Bioplastic, Biodegradable, Eco-friendly, Environment, Sustainable.

I. INTRODUCTION

The modern industrialized era involves an ever-increasing need for plastic products, but because plastics are rarely recycled and are not biodegradable, plastic pollution or "white pollution" has resulted. By 2050, the usage of petroleum-based plastics would account for 20% of worldwide annual oil consumption, necessitating the need for a creative solution to prevent plastic pollution.

Environmental pollution occurs due to improper waste disposal of plastics products and this has caused direct deterioration towards the environment, entanglement and death of aquatic organisms, sewage system blockages in towns and cities resulting in an ideal environment for mosquito breeding and diseasecausing micro-organisms (Acquavia, M. et al .,(2021), Eriksen ,M.et al., (2014), Silva, A.L. P . et al.,(2020). Improper waste disposal of plastics has also led to greater costs in cleaning contaminated water (Shams, M.et al., 2021). Burning plastic releases toxic gases such as dioxin, furan, mercury and polychlorinated biphenyls which are extremely harmful towards the environment and other life-threatening illnesses such as neurological damage, cancer, damage to respiratory system and disrupts reproductive thyroid (Verma, R.et al., (2016), Karn, S. K. (2021)). Microplastic buildup in people has resulted in serious medical disorders such as bone osteolysis, tissue inflammation, organ lesions, undesired cell necrosis, and even DNA mutation (Choudhury, A. et al., (2018).Currently, bioplastics represent for 10-15% of total worldwide plastic manufacture (Venkatachalam, H., et al., (2020), Ashter, S. A.et al., (2016). Bioplastics are classified as (i) polymers recovered from biomass, (ii) microorganism-produced polymers, and (iii) polymers synthesised from bio-derivative monomers (Venkatachalam, H., et al., (2020), Ashter, S. A.et al., (2016).

According to reports investigated by the United States Environmental Protection Agency (2020), approximately 34 million metric tonnes of plastics leak into the aquatic environment each year the vast majority of such plastics are the result of a lack of an efficient disposal system and a low recycling rate. As a result, recycling practices should be used as a means of managing waste to lessen the plastic load on the environment. Recycling gives us chances to minimize oil consumption, carbon dioxide emissions, and trash disposal volumes. However, recycling practices are occasionally connected with substantial issues/challenges, such as high labor costs and insufficient infrastructure for processing mixed plastic trash. Due to ineffective waste management procedures and this amount is anticipated to triple by 2040 if suitable waste management treatment solutions are not implemented.

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Furthermore, due to the lack of separate recycling streams, all types of plastic confront challenges while recycling, posing the task of sorting out the desired plastic trash for proper recycling. Furthermore, the presence of toxic chemicals in plastics makes recycling challenging. Another issue with recycling is that the plastic quality (in terms of chemical and physical qualities) is lower than that of the original, limiting its future usage and shelf life. (Joseph, B., et al (2021), Chidambarampadmavathy, K., et al., (2017)

- According to 2018 data, only 25% of plastic gets recycled, 22% is burned, and the remaining ends up in landfills. During the COVID-19 pandemic, there was an unanticipated rise in plastic usage (plastic used in medical kits, packaging, and face masks), which increased plastic manufacturing. Only 8.5% of the 35.68 million tonnes of plastic generated in the United States is recycled, with the balance being burned or landfilled. Because of current inefficient waste management practices, roughly 12 billion tonnes of plastic rubbish will wind up in the environment by 2050 (Silva, A. L. P., et al., (2020), Shams, et al., (2018).

- PLA, PHA, PHB (polyhydroxybutyrate), starch, and cellulose are examples of biodegradable plastics made from plants. These bioplastics are in high demand since they are biodegradable and manufactured from bio-based components (plants and microorganisms).

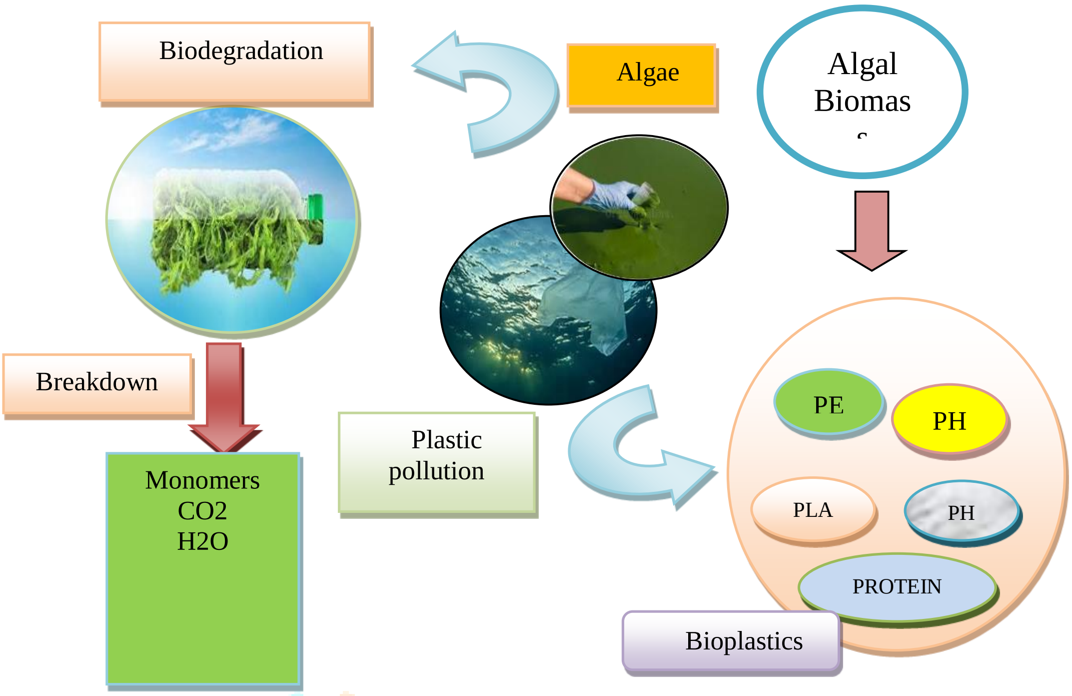

Figure 1: Algae for plastic biodegradation and bioplastics production (Wen Yi et. al., (2020)

II. BIOPLASTICS

A polymeric material is called bioplastic if it is either bio-based or manufactured from renewable components with biodegradability potential (Mekonnen et al. 2013). Bioplastics are certain forms of bioresource-based polymeric materials that are regarded as environmentally and economically viable to replace conventional petrochemical plastics. Many environmental difficulties associated with plastics can be avoided by employing biopolymers and bio-based fibers derived from bioresources and renewable wastes. Bioplastics are thought to be superior polymers to synthetic plastics due to their biocompatibility and biodegradability, making them ideal for use in packaging, biomedical, and other value-added industrial applications (Pathak et al. 2014; Prasanth et al. 2021).

2.1. Types of Bioplastics Derived from Algae

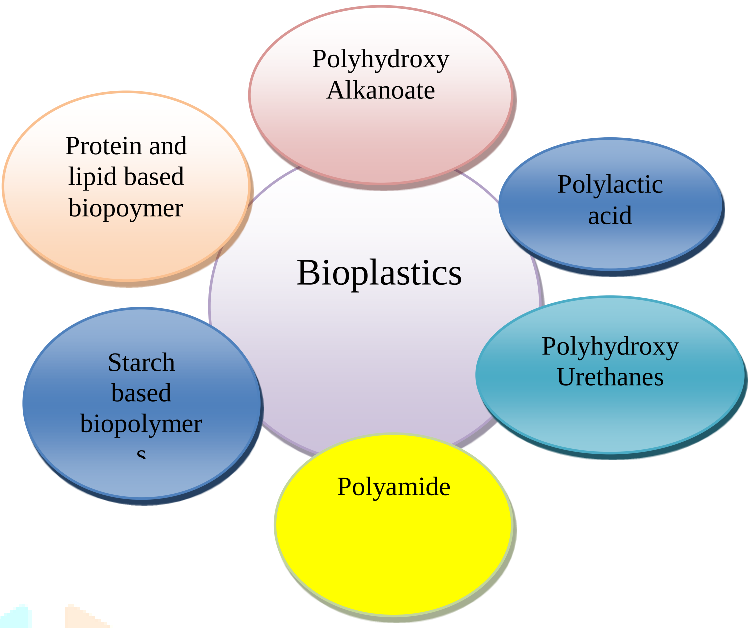

Figure- 2: Showing types of bioplastic

2.1.1. Polyhydroxyalkanoates (PHAs):

Polyhydroxyalkanoates (PHA) are aliphatic polyesters that have been promoted as a good substitute for plastics generated from petroleum-based compounds (Naser, A. Z., et al., (2021).
It is a member of the polyhydroester family, which includes 3-, 4-, 5-, and 6-hydroxyalkanoic acids. Bacteria and plant biomass both synthesize PHAs. The polyhydroxyalkanoate synthase (PhaC), acetoacetyl-CoA reductase (PhaB), and acetyl-CoA acetyltransferase (PhaA) enzymes are the primary players in the PHA biosynthesis pathway. PHA is synthesized by certain bacteria, such as *Pseudomonas putida* and *Ralstonia eutropha* and can be exploited as an energy and carbon storage substrate (LD, P. et al., (2020), Saleel, C. A.et al., (2022).

2.1.2. Polysaccharides and alginate-based bioplastics:

Complex polysaccharides such as starch from rice, corn, wheat, and potato have been extensively explored for usage in bioplastics (Bilo, F., et al., (2018), Venkatachalam, H., et al., (2020), Jiang, T.,et al.,(2020), Mohan, A.et al.,(2022).Starch-based feedstocks are chosen because they are low-cost, biodegradable, and can be processed using standard processing equipment Venkatachalam, H., et al., (2020), Jiang, T., et al., (2020).
Because starch-based bioplastics are hydrophilic, they are unsuitable for food packaging. (Jiang, T.et al., (2020). The degree of amylopectin fragmentation reduced as moisture content increased (20-45%). Rice straw, which contains a high concentration of cellulose (32-47%), hemicellulose (19-27%), and lignin (5-24%), is also a suitable feedstock (Bilo, F., et al., (2018).Because cellulose-based bioplastics are more expensive to produce than starch-based bioplastics, their usage is still limited today (Venkatachalam, H., et al.,(2020).

2.1.3. Protein-based bioplastics:

Protein sources such as whey, soy, egg white, and wheat gluten could be used to make bioplastics. Soybeans contain 40-55% protein, allowing them to be molded into films and plastics (H. Venkatachalam.et al., (2020). These proteins revealed properties that could be exploited to build polymers with biological applications. Bioplastics derived from egg white and wheat gluten have properties such as high-temperature resistance, good water absorption and retention and have been used in active drug delivery systems, absorbents and food packaging. Jones and colleagues (Jones, A., et al., (2015).

III. CHALLENGES IN ALGAE-BASED BIOPLASTICS

Bioplastics are gaining popularity due to their eco-friendliness, good impact on the environment by reducing greenhouse gas emissions, and, most significantly, the threat to marine and human health. Despite the obvious benefits of bioplastics, several obstacles lie ahead:

• High manufacturing costs (twice those of ordinary synthetic polymers (Jim, P.et al., (2014).
• Inability to complete deterioration in all possible states.
• Need to thoroughly explore and develop all potential best solutions for negative environmental impacts, since greenhouse gas emissions (methane) are a major concern nowadays.
• Discovering new, low-cost raw materials for economical manufacture as an alternative to plant-based bioplastics in order to safeguard food sources and thereby move the world closer to sustainable development.
•Enhancement of algae-based biopolymer routes (expensive and inefficient manufacturing method) for a more sustainable future.
• Inadequate water resistance may impede with bioplastic applications (Cherry, C. E., et al., 2020).

IV. ALGAE AS A FEEDSTOCK FOR BIOPLASTIC

Because of their rapid growth, high lipid content, and capacity to collect carbon dioxide through photosynthesis, algae have received a lot of interest as a potential feedstock for bioplastic manufacture. This section provides an overview of algal diversity, growing methods, algae biomass composition and extraction/processing procedures for bioplastic manufacture.

The rapid growth of algae makes it a prime candidate for use as a feedstock for bioplastics. Algae is a remarkably effective supplier of raw materials since it can quickly quadruple its biomass. This quick growth enables frequent harvesting and ongoing production, guaranteeing a consistent supply of feedstock for bioplastic synthesis. Additionally, freshwater, saltwater, and even wastewater are all conditions in which algae can be grown. Due to its adaptability, algae cultivation is a sustainable method of producing bioplastics and eases the burden on land and freshwater resources. Additionally, in nutrient-rich wastewater streams, algae can grow and produce feedstock for bioplastics while also treating the wastewater. During photosynthesis, algae have the unusual capacity to absorb carbon dioxide (CO2). Algal-based bioplastics can aid in reducing greenhouse gas emissions and achieving carbon neutrality by using CO2 emissions from industrial operations, such as those at factories or power plants. Because of their potential to sequester carbon, algae are a sustainable option for the manufacturing of bioplastics.

Researchers have concentrated on extracting and using particular components, like lipids or polysaccharides, from algae-based bioplastics. Algal lip extract can be utilized to create biodegradable polyesters, and polysaccharides can be used to create biopolymers with a variety of uses. These bioplastics made from algae have characteristics that are comparable to those of traditional plastics with the added benefit of being renewable and biodegradable. Algae-based bioplastics continue to face difficulties despite their many advantages. Research is still being done on expanding the culture of algae and improving the extraction methods. In order to ensure commercial viability, cost-effectiveness and competition with alternative feedstocks must also be taken into consideration.

Algae is a very promising feedstock for the creation of bioplastics, to sum up. It is a desirable choice for the production of sustainable bioplastics due to its quick growth, capacity to store carbon dioxide, and adaptability in cultivation. Algae-based bioplastics may be able to significantly reduce our reliance on fossil fuels and reduce plastic pollution with further technological development and additional funding(Cheah.et al., 2023)

V. BIOMASS COMPOSITION OF ALGAE

Algae biomass contains a variety of components that can be used to make bioplastics, including.

Carbohydrate

Algae contain a variety of carbohydrates, including cellulose, hemicellulose, and starch, which can be used as a carbon source for bioplastic.

Lipids

Algae with high lipid content can be removed and processed into bioplastic or utilized as a precursor for bio-based polymers.

Proteins

Algae biomass includes proteins that can be processed and used as a feedstock for biobased monomers or in bioplastic formulations.

VI. PROCESSING TECHNIQUES FOR ALGAE-BASED BIOPLASTICS:

VI.I. Blending Algal Biomass with Starch

Starch, which has a long chain of amylopectin and amylose, has good film-forming capabilities and is widely employed in a variety of industrial products, including bioplastics. (Lörcks, J et al., (1998). Starch-based bioplastics are frequently renewable, biodegradable, and cost-effective. Most crucially, by increasing the starch to microalgal biomass ratio, starch blend bioplastics are biodegradable at a faster pace (Ratto, J.A.et al., (1999).

VI.II. Blending with other materials

Blending is the most popular method for modifying and improving the physical properties of a polymer. Multiple polymers are mixed together to achieve a homogenous polymer phase. Blending microalgae biomass with conventional plastics or petroleum plastics could increase the mechanical strength of microalgae-based polymers (W.Y. Chia, et al., (2020).
Microalgae biomass, on the other hand, can be blended with other materials, such as petroleum plastics, natural products (cellulose or starch), or polymers, when making bioplastics to extend their lifespan, improve their properties, and improve their mechanical performance (Rahman, A., et al., (2017). Algae biomass can be used to produce blended materials such as PLA, PHA, cellulose, starch, and protein. (Shi et al., (2012). Observed that the mechanical properties of microalgae-containing plastic films were comparable to those of polyurethane or PE plastic films, despite the drawback of low tensile strength, notably elongation at break. Aside from that, an investigation by (Otsuki et al., (2004).

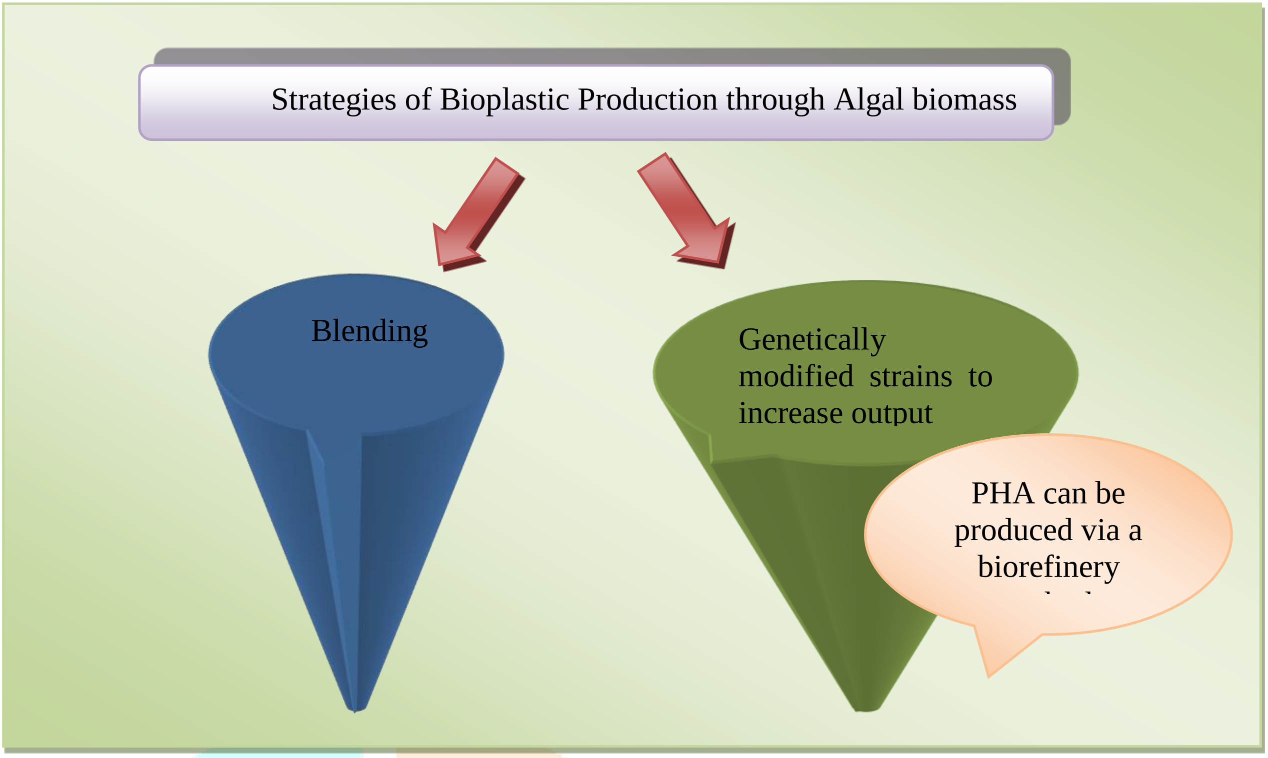

Fig.3 Different strategies of bioplastic production using algal biomass (Bulota, M. and Budtova, T.et al., (2015).

VII. POTENTIAL OF ALGAE AS A SOURCE OF BIOPLASTICS

- Bioplastics are plastics that are created entirely or partially from biomass or renewable sources, such as food crops, and serve the same purpose as petroleum-based plastics. Bioplastics can be manufactured from a variety of materials with varying characteristics. Bioplastics are classified into three categories.

- PE, PP, PET, polytrimethylene terephthalate (PTT), or polyester elastomers (TPC-ET) are examples of bio-based but non-compostable polymers.

- Polylactic acid (PLA), PHA, starch and cellulose are examples of bio-based and degradable polymers. Biodegradable fossil resource-based plastics: PBAT (Polybutylene Adipate Terephthalate).

VIII. APPLICATION OF BIOPLASTIC

Category	Potential application	References
Biodegradable implants	Because of their biodegradability, biopolymers such as polyhydroxyalkanoates have had a significant impact on modern pharmaceuticals.	Ulery et al. (2011)
Drug carriers	Polyhydroxyalkanoate can be used as a raw material to make nanoparticles and tablets and as a scaffold for eluting medicines.	Xionget al.,(2012),Nigmatullin et al., (2015)
Biomedical devices	Polyhydroxyalkanoate is found in meniscus repair devices, adhesion barriers, staples, screws, stents, repair patches, rivets, and other medical devices.	Lobler et al. (2002); Volova et al. (2003); Valappil et al. (2006); Kenar et al., (2010)
Antibacterial	3-hydroxy alkanoic acids can be employed as a building component in the pharmaceutical industry.	Babel et al., (2001)

IX. LCA (LIFE CYCLE ASSESSMENT) ANALYSIS OF BIOPLASTICS:

It should be emphasized that the computation of the life cycle assessment (LCA) is highly reliant on, but not limited to, the system boundary, products analyzed, as well as process variables and routes. Previous investigationThe increased manufacture of bio-based plastics necessitates extensive environmental studies. LCA is a quantitative method for assessing the potential environmental consequences (both positive and negative) of items over the course of their life cycle. There were two types of studies used in the bioplastic LCA study: Cradle-to-grave (downstream product process) includes an end-of-life assessment assessing the impact of the recycling or biodegradation process/ultimate removal of the product, followed by an analysis of the bioplastic impact on the environment. Although LCA studies do not represent the actual process or the correctness of a product evaluation, numerous parameters might be examined to provide sufficient information (usually, assumptions are made (Walker, S, et al., (2020).

The culture processes were heavily worked on, with an interesting tradeoff between high productivity (and control) in photobioreactor (PBR) vs a lower energy input and environmental imprint in an open-pond reactor. However, there has been very little research on algal bioplastics. Furthermore, any bioplastic material created with sustainability in mind should address biodegradability. Once the material begins to disintegrate, there will very probably be some CO_2 released into the environment. (S.O. Cinar, et al., (2020).

X. FUTURE PERSPECTIVES

Algae as a feedstock for bioplastics holds a lot of potential and has a wide range of potential applications. Here are some crucial points to think about:

Improvements in Algae farming: As technology develops, there will probably be advancements in algal farming methods. This entails improving the growth environment, raising biomass productivity, and creating more effective harvesting techniques. These developments will help algae-based bioplastic production scale up and become more economical.

Using genetic engineering, it is possible to improve the beneficial characteristics of the algae strains used to make bioplastic. Algal genomes can be modified by scientists to boost growth rates, increase lipid content, and customize the makeup of biopolymers made by algae. Furthermore, initiatives for strain selection and breeding can aid in the discovery and development of high-yielding algae species specifically suitable for the manufacturing of thermoplastics.

Integration with Other Industries: To foster symbiotic connections, algae farming for bioplastics can be combined with other industries. For instance, wastewater treatment facilities can use algae to remove nutrients from effluent and produce biomass for the creation of bioplastics at the same time. These partnerships can increase the bioplastics derived from algae's sustainability and commercial viability.

The environmental problems caused by traditional plastics can potentially be solved by algae-based bioplastics. Reduced carbon footprint, less dependency on fossil fuels, and the potential for biodegradability are just a few benefits of using algae as a feedstock for bioplastics. Algae-based polymers must yet overcome some obstacles before they can become widely used in commerce.

The best ways to cultivate and collect algae, scaling up manufacturing, and maintaining cost parity with conventional plastics are among the major concerns. To guarantee the safety and quality of bioplastics derived from algae, regulatory frameworks and standards also need to be established.

Technical Advances: Ongoing research and development activities will probably result in technology advances that speed up the process of turning algal biomass into bioplastics. This includes improvements in processing technology, polymerization procedures, and extraction techniques. The effectiveness, caliber, and adaptability of the manufacture of bioplastics based on algae will all benefit from these advancements.

XI. CONCLUSION:

The environmental problems caused by traditional plastics can potentially be solved by algae-based bioplastics. Reduced carbon footprint, less dependency on fossil fuels, and the potential for biodegradability are just a few benefits of using algae as a feedstock for bioplastics. Algae-based polymers must yet overcome some obstacles before they can become widely used in commerce.

The best ways to cultivate and collect algae, scaling up manufacturing, and maintaining cost parity with conventional plastics are among the major concerns. To guarantee the safety and quality of bioplastics derived from algae, regulatory frameworks and standards also need to be established.

Despite these difficulties, algae as a feedstock for bioplastics has a bright future. Unlocking the full potential of algae-based bioplastics will depend heavily on ongoing research, technological developments, and partnerships between government, business, and academic institutions. Algae-based bioplastics have the potential to revolutionize the plastics sector, lessen their negative effects on the environment, and help create a more sustainable future with continued work.

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