



REVIEW ARTICLE

Role of microalgae as a sustainable alternative of biopolymers and its application in industries

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ARTICLE HISTORY

Received: 23 February 2023

Accepted: 12 July 2023

Available online

Version 1.0 : 13 August 2023



Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care etc. See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

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CITE THIS ARTICLE

Dimri R, Mall S, Sinha S, Joshi N C, Bhatnagar P, Sharma R, Kumar V, Gururani P. Role of microalgae as a sustainable alternative of biopolymers and its application in industries. Plant Science Today (Early Access). <https://doi.org/10.14719/pst.2460>

Abstract

The escalating accumulation of petroleum-based polymers has depleted resources and raised environmental concerns due to their non-recyclable and non-biodegradable nature. Consequently, there has been a growing interest in bio-based plastics, particularly algal-based biopolymers, which offer recyclability and eco-friendliness. Algae-derived polymers have distinct advantages, such as autotrophic growth reducing greenhouse gas emissions, rapid growth rate, low nutritional requirements, and resilience to harsh environments. Additionally, algae exhibit higher photosynthetic potential (10 -20%) compared to terrestrial plants (1%-2%). The range of algal-derived polymers includes alginate, laminarin, fucoidan, carrageenan, agar, ulvan, polyhydroxyalkanoates (PHA), and poly-(Hydroxybutyrate) (PHB). However, further efforts are required to implement them on a large scale. This review highlights algae's potential as a raw material for biopolymer production, exploring their characteristics and applications in diverse industries like food and pharmaceuticals.

Keywords

Algae; biopolymers; pharmaceutical Industry; food industry

Introduction

Various polymers exhibit exceptional material qualities, finding applications in lightweight packaging, agriculture for improved crop yield, cosmetics, detergents, and novel opportunities (1, 2). The escalating environmental damage caused by extensive production of synthetic polymers has spurred the pursuit of eco-friendly materials (3). Growing emphasis on sustainability has driven the emergence of biopolymers—bio-based and biodegradable polymers (4). To address synthetic polymers' persistence and non-degradability, incorporating components for accelerated disintegration has gained prominence (5). Biopolymers have garnered significant attention among scientists and researchers due to their potential environmental benefits and concerns related to human health. These polymers, derived from living organisms, possess unique properties like renewability, biocompatibility, and biodegradability (6). They are considered promising alternative to fossil-based polymeric materials, but their increasing use has raised certain environmental issues (7).

In general, bio-based polymers are sourced from renewable materials such as plants, microorganisms, bacteria, and algae. They can be obtained directly from these sources or synthesized from monomers and then polymerized. Some well-known examples of bio-based polymers include polylactic acid, polyhydroxybutyrate, poly L lactide, polyhydroxyalkanoates (PHAs), polypropylene (PP), and polyamide (Fig. 1) (8). Moreover, research has shown that cyanobacteria and microalgae are particularly promising sources for cellulose, PHAs, proteins, and carbohydrates (specifically starch) for the production of bioplastics (9). For instance, certain cyanobacteria species like *Spirulina* sp., *Synechocystis* sp., *Oscillatoria* sp., *Nostoc* sp., and *Calothrix* sp. have demonstrated PHA content ranging from 1% to 10%, depending on the species (10). Additionally, microalgae species like *Chlamydomonas reinhardtii* and *Klebsormidium flaccidum* have been found to contain high levels of starch, which can be utilized in bioplastics manufacturing (9, 11). The appeal of bio-based polymers lies in their improved mechanical properties and their wide range of applications in electronics, medical devices, food packaging, and energy sectors (12). As research and technology continue to advance, biopolymers hold promise as sustainable materials with reduced environmental impact, paving the way for a greener and more ecologically responsible future.

This review concentrates on the synthesis of biopolymers derived from various algal species and their application in diverse industrial sectors, including pharmaceuticals and food. The analysis also emphasizes the cultivation conditions and system prerequisites for efficient microalgae-based biopolymer production.

Furthermore, the characteristics, extraction processes, and cost-effectiveness of biopolymers sourced from different algal species are elucidated. Additionally, the review discusses the research gaps that need to be addressed to facilitate the commercialization of algal-derived biopolymers across various industrial sectors.

Review Methodology

This review-based study aimed to explore the utilization of microalgae as a promising alternative for biopolymer production and their applications in various industrial sectors. To achieve this, we conducted a comprehensive search of scientific publications in reputable electronic databases such as Web of Science, SCOPUS, SciFinder, DOAJ, and MEDLINE/PubMed. The search was performed using a set of specific keywords, including "Microalgae," "Cultivation of algae," "System requirements," "Biopolymer production," "Natural sources of biopolymers," "Production of biopolymers from microalgae," "Microalgal starch," "Structure of PHA," "Extraction process," "Cost affordability of algal biopolymers," "Utilization in industries," "Food industry," "Pharmaceutical industry," and "Future perspectives." Only studies that investigated the effect of different cultivation conditions or stress conditions on the synthesis and yield of biopolymers in various algal species and their practical applications in industrial sectors were considered for inclusion. We excluded experimental studies, duplicates, and irrelevant test substances to ensure the integrity and validity of our analysis. The relevant information extracted from the selected studies was summarized and presented in figures and tables. To

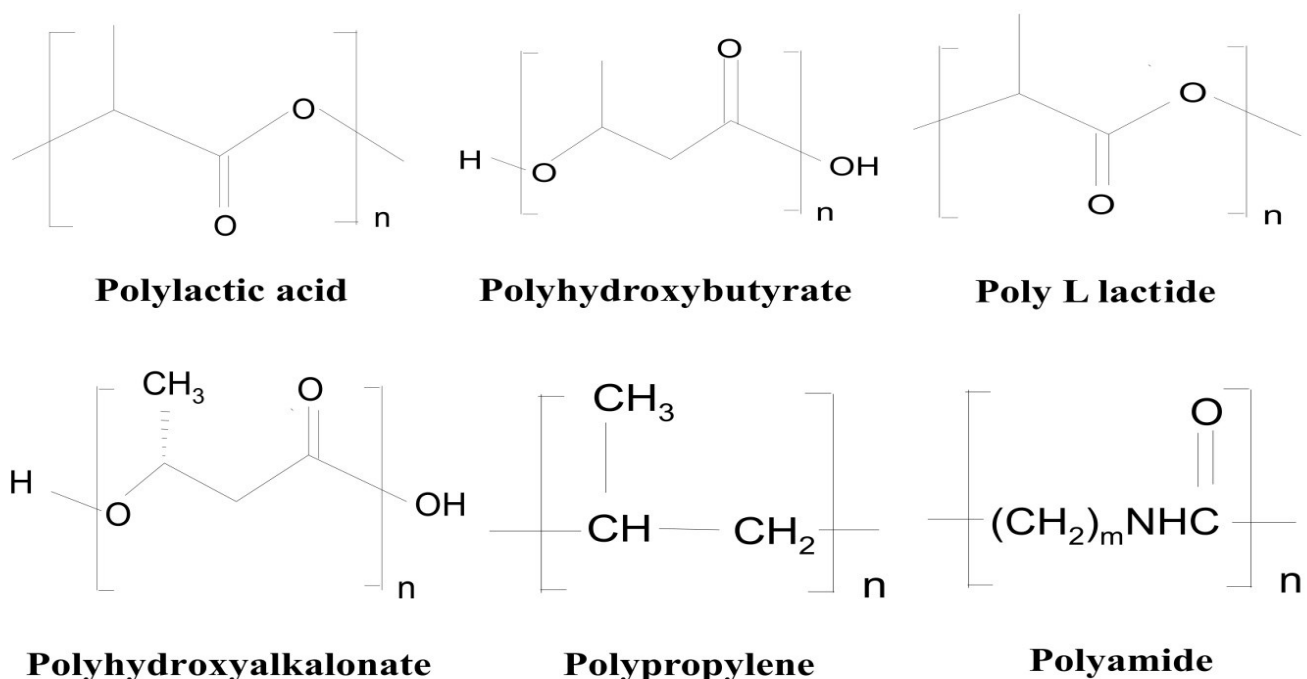


Fig. 1. Molecular structure of different biopolymers

enhance the visual representation of molecular structures and illustrations, we employed the software "BioRender" for creating images and "Chem Draw" for drawing molecular structures. By employing this systematic approach, we aimed to provide a scientific and comprehensive review of the current state of knowledge regarding microalgae-based biopolymer production and its potential applications in different industries. This study contributes to advancing our understanding of the sustainable and cost-effective utilization of microalgae-derived biopolymers in various industrial sectors.

Conventional sources of biopolymers

The production of biopolymers is traditionally classified into three generations: first, second, and third generation (13). However, the first and second generations may result in the degradation of plastics into microplastics, posing environmental risks. To address this issue, the third generation focuses on using natural animal or plant-based feedstock to produce biodegradable polymers without leaving any traces of microplastics or by-products in the environment. Despite the promising approach of utilizing

terrestrial crops like plants, corn, and potatoes as natural sources for third-generation biopolymers, there are several associated challenges and flaws. One of the primary concerns is the fuel-versus-food debate, where the use of crops for biopolymer production competes with their utilization for food production, potentially impacting food security. Additionally, this process requires significant arable land, leading to potential land-use conflicts and ecological disruptions. The demand for nutrients and water is also high, raising concerns about resource depletion and environmental impact (14, 15). Table 1 and Figure 2 illustrate some of the main conventional sources used for biopolymer production.

Biopolymer from microalgae and its characteristics

Modernization has facilitated the commercialization of petroleum-derived chemicals like PVC, PP, PE, etc., in the current market. However, their long-term use has significantly disrupted environmental equilibrium, necessitating the search for suitable substitutes (16). To address this issue, scientists are now exploring the intersection of economics and biology to enhance

Table 1. Conventional Biopolymers Obtained from Different Sources

Biopolymer	Sources	Species	Application	References
Hyaluronic acid	Bacteria	<i>Streptococcus</i> sp.	Drug delivery, cosmetic, Visco-supplementation, and repair of tissue	(70)
Cellulose	Bacteria	Betaproteobacteria, Gram-positive bacteria	Wound dressing and in food industry	(70)
Gellan	Bacteria	<i>Sphingomonas</i> sp.	Food additive, culture media additive for encapsulation	(70)
Polyhydroxy alkananoates (PHA)	Microalgae	<i>Calothrix scytonemicola</i>	Production of bioplastic material used to cast thin and brittle plastic film.	(25)
Polyhydroxy alkananoates (PHB)	Microalgae	<i>Nostoc muscorum</i>	Replacement of petrochemical source of polymers	(30)
Heteropolysaccharide	Fungi	<i>Coprinus comatus</i>	Antioxidant; hypoglycemic	(71)
Heteroglucan	Fungi	<i>Lasiodiplodia</i> sp.	Antimicrobial; antioxidant; immunomodulatory	(72)
Mycocel	Plant cellulose And Fungal biomass	Fungal species: <i>G. applanatum</i> , <i>F. fomentarius</i> , <i>A. bisporus</i> , <i>T. versicolor</i> , <i>L. lepideus</i> , <i>P. squamosus</i> , <i>F. betulina</i> Plant: Kraft fibre, Hemp fibre from <i>Cannabis sativa</i>	The biopolymer has significant mechanical properties, air permeability, and virus filtration efficiency. Based on the properties of these biopolymers, they can be utilised in the food packaging industry and also in preparation of gas permeable membranes.	(73)
Xylan	Plant	Zea mays (from corncobs), Fagus species (from beech tree wood)	Xylan based nanocarriers found active against <i>Botrytis cinerea</i> , a fungus having devastating impact on viticulture and horticulture.	(74)
Collagen and Keratin	Animal	Egg shell of <i>Salvator merianae</i>	Provide Biomaterials.	(75)

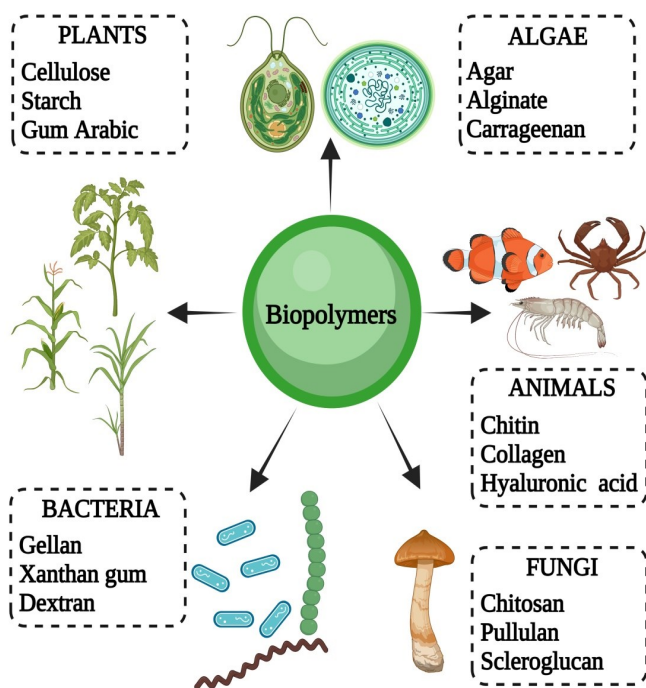


Fig. 2. Possible Natural Sources of Biopolymers

biodiversity and society. The focus is on discovering novel biodegradable substances sourced from biological resources. Among potential candidates, algae have emerged as highly promising. They possess several advantageous characteristics such as minimal nutrient requirements, rapid growth rates, and the ability to thrive without the need for vast arable land (17-19). Algae are ubiquitously found in various environments, ranging from marine to freshwater, and can be cultivated throughout the year. Moreover, they can be cultivated using heterotrophic, mixotrophic, and autotrophic methods, both on a large scale and in laboratory settings. By subjecting algae to nutrient insufficiency or other cellular stress, lipid, hydrocarbon, and polysaccharide production can be enhanced (20). Adopting algae as the primary source for biopolymer production offers the advantage of not adversely affecting their biodiversity in natural habitats. Algae are easily cultivated and widely available microorganisms. The resulting algal-based biopolymers possess high nutritional value and can be utilized in various industrial applications. Phycocolloids, such as agar, alginate, and carrageenan, extracted from marine algae, serve as essential stabilizers, emulsifying agents, and gelling agents in numerous industries (21). Their use contributes to an eco-friendly approach that promotes sustainable resource utilization.

Macroalgae and microalgae together constitute a diverse group of algal species, with their collective count exceeding one million. Among them, microalgae hold greater significance and show promising potential in biopolymer production (22, 23). Due to their ability to undergo photosynthesis even in challenging environments such as marine environments or infertile lands where traditional agricultural crops cannot thrive, microalgae offer a possibility of replacing petroleum-derived chemicals. Additionally, microalgae exhibit various metabolic pathways that can be exploited to produce

substantial amounts of bioplastics, making it an economically viable approach for efficient biopolymer production and other high-value added products. One key area of research focuses on the production of biofuels from sustainable microalgal feedstock, offering an efficient alternative energy source to fossil fuels (16, 24). Recent research findings have demonstrated the production of biopolymers from algae, with polyhydroxyalkanoates (PHA) being one of the prominent biopolymers with extensive industrial applications. Microalgal strains like *Calothrix scytonemica* (25), *Synechococcus elongatus* (26), and *Synechococcus subsalsus* (27) have shown the ability to produce PHA. Another significant biopolymer is polyhydroxybutyrate (PHB), which is produced by strains such as *Spirulina* sp. LEB 18 (28), *Chlorella vulgaris* (29), and *Nostoc muscorum* (30). These findings highlight the potential of microalgae in advancing sustainable biopolymer production and offer a pathway towards a more eco-friendly and renewable resource-based industrial approach.

Biopolymers, such as Polyhydroxyalkanoates (PHAs), are intracellularly synthesized polyesters of hydroxy alkanooates produced by bacterial and algal cells (31). These biopolymers exhibit several desirable characteristics, making them environmentally friendly alternatives to fossil fuels and non-degradable plastics (31, 32). Some of their key properties include high hydrophobicity, biodegradability, thermoplasticity, elasticity, inertness, non-toxicity, high optical purity, and improved resistance to degradation caused by ultraviolet radiation (31, 32). A microalgal species, *Leptolyngbya valeriana*, is utilized for PHA production and has been found to possess higher thermal stability compared to other PHAs (9). The glass transition (T_g) and melting temperature (T_m) of the synthesized bioplastics fall within the range of 4–10 °C and 79–116 °C, respectively (9). The basic structure of PHAs consists of monomer units of (R)-hydroxy fatty acids connected by ester bonds, with a side chain of saturated, unsaturated, branched, or substituted alkyl groups (33). Different PHAs can be produced depending on the strategies and strains used in the production process. For instance, *Cupriavidus necator* produces short-chain-length PHAs, such as poly (3-hydroxyvalerate) and (3-hydroxybutyrate), which exhibit rigidity and brittleness, making them unsuitable for biomedical and packaging film applications (34). On the other hand, *Pseudomonas mendocina* produces poly (3-hydroxyoctanoate) with a medium chain length of 6-14 carbon atoms, which imparts elastomeric properties, albeit with moderate mechanical strength (33). Additionally, *Pseudomonas aeruginosa* produces poly(3-hydroxy pentadecanoate) with a 15-carbon chain length (33). The variation in PHA characteristics can be attributed to different production strategies, strains, and nutrient concentrations in the growth media (31, 35). Some researchers have reported enhanced PHA growth in media deprived of certain nutrients or by using non-fastidious microalgal strains like *Botryococcus braunii*, which is estimated to have the highest content of accumulated PHAs (31). Various studies have been conducted to

optimize PHA production in microalgae. For instance, *Synechocystis salina* was cultured in BG-11 media under nutrient-limiting conditions, resulting in a polymer content of 5.5-6.6% in dried cells (36). Similarly, *Synechococcus elongatus* was cultivated under mixotrophic phosphate and nitrogen stress conditions, yielding a PHA production of 17.15% in nitrogen-deficient medium supplied with 1% sucrose as a carbon source. Comparatively, the PHA yield was 7.02% in phosphate-deficient medium with 1% fructose as the carbon source (26). However, the yield obtained from algae (17.15%) was lower than that of bacterial PHA production systems. Therefore, further efforts are required to enhance PHA yields in algae.

Costa et al. (27) conducted a study to investigate the impact of nitrogen deficiency on the production and properties of polyhydroxyalkanoates (PHAs) by different microalgae species: *Synechococcus subsalsus*, *Spirulina* sp. LEB-18, and *Chlorella minutissima*. After a 15-day cultivation period, the researchers observed that *Synechococcus subsalsus* and *Spirulina* sp. LEB-18 exhibited the highest accumulation of PHAs, with concentrations of 16% and 12% (dry weight), respectively. However, *Chlorella minutissima* did not produce any PHAs under nitrogen-deficient conditions. The PHAs produced by *Spirulina* sp. LEB-18 and *Synechococcus subsalsus* exhibited distinct physical and thermal properties, highlighting the influence of the producing strain on PHAs' characteristics. Microalgal starch is a biopolymer consisting of complex carbohydrates, namely amylose and amylopectin chains linked by α -1,4 and α -1,6 glycosidic bonds, respectively. It serves as a potential feedstock for the production of biodegradable and photosynthetically efficient bioplastics known as thermoplastic starch. These bioplastics typically contain 40% starch content by weight (37-40). The critical properties that determine the industrial suitability of starch biopolymer include the amylose-amylopectin ratio, size of starch granules, thermal properties, and crystallinity. *Chlorella sorokiniana*, a microalgal strain, produces starch in relatively lower amounts but demonstrates higher biomass productivity compared to plant species. Approximately 80% of the examined starch granules from *Chlorella sorokiniana* were found to have a size within the range of 0.8-5.3 μ m, making them ideal for research involving small-sized granules and showing promising enrichment potential by this microalgal strain (38). Another study on *C. sorokiniana* reported an average granule size of 1.5 μ m, making it the smallest reported size and rendering it suitable for application as a flavor carrier in the food industry (35).

Algae cultivation conditions and system requirements

Algal species are traditionally known to be photoautotrophic, relying on a few nutrients and primary abiotic conditions for cultivation. However, the development of algal cultivation technologies is ongoing, as the environment of cultivation and nutrient composition in the growth medium significantly impact their growth and production of bioactive compounds (41-

45). Particularly, for biopolymer production, algae are cultivated in two consecutive stages. The initial stage involves continuous culture with sufficient nitrogen in the nutrient medium to achieve high cell density. A small portion of the culture from this phase is then transferred to the second stage, where the cells experience nitrogen insufficiency or salinity stress (46, 20). During this stage, biopolymer production takes place. Subsequently, the obtained algal biomass containing essential precursors or biopolymers can be converted into valuable products using biochemical, mechanical, enzymatic, or chemical treatment methods (47). The choice of cultivation system significantly influences algae growth. Two commonly practiced systems for algal cultivation are closed and open systems. Open pond systems, which include shallow artificial ponds or natural habitats, are frequently mixed using paddle wheels or rotating arms and have long been established for algal cultivation. These systems are characterized by moderate power requirements, reduced capital and operating costs. They comprise raceway ponds, circular ponds, and tanks. However, open systems are more susceptible to contamination and pollution, experience water depletion through evaporation, heavily rely on weather conditions, and have limited control over critical parameters such as temperature, illumination, nutrient levels, and pH, leading to low reproducibility. The main limitations stem from inadequate mixing, resulting in limited illumination and unsatisfactory supply of carbon dioxide gas (48).

Closed photobioreactors (PBRs) present a viable alternative to open pond systems due to their ability to effectively regulate cultivation parameters and overcome contamination issues. The closed photobioreactor system can be classified into three main types: vertical column, closed tubular, and flat plate designs. These photobioreactors enhance biomass yield and protect the culture from microbial contamination by allowing precise control of temperature, pH, illumination, nutrients, and the release of oxygen gas produced during photosynthesis. Moreover, the controlled conditions facilitate gentle mixing, ensuring even distribution of cells, CO₂ gas, and essential nutrients. This continuous movement of cells prevents their attachment to vessel walls, maintaining optimal illumination levels for photosynthesis (48). Compared to open pond systems, closed photobioreactors are gaining popularity and are being increasingly employed for large-scale outdoor cultivation of microalgae to produce biopolymers. However, it is worth noting that these systems are associated with higher costs and energy consumption. Consequently, there is a tendency to limit their exposure to sunlight while still enabling the cells to carry out photosynthetic activities effectively. To address this challenge, some researchers have explored the use of LED lights as a cost-effective alternative to traditional artificial lighting methods (41).

Extraction process and cost affordability of biopolymers from micro and macroalgae

In recent years, there has been a significant focus on the extraction process and cost-effectiveness of biopolymers

from micro and macroalgae, mainly due to their potential applications across various industries. The extraction process involves several essential steps, starting with biomass collection, followed by pretreatment, extraction, purification, and finally formulation. To begin, the harvested algal biomass undergoes various pretreatment methods, aimed at removing impurities and enhancing the overall efficiency of extraction. Commonly practiced pretreatment techniques include drying, grinding, and cell wall disruption. Following pretreatment, the extraction of biopolymers from algae can be accomplished using different methods. These methods may involve solvent extraction, enzymatic hydrolysis, or physical approaches like ultrasound and microwave-assisted extraction (50).

Solvent extraction is a widely utilized technique in which organic solvents dissolve and separate biopolymers from biomass. Enzymatic hydrolysis involves using specific enzymes to break down the complex structure of algae biomass, releasing the biopolymers. Physical methods employ mechanical forces or energy to disrupt cell walls, facilitating biopolymer release (50, 51). Once extracted, biopolymers undergo further purification and processing to achieve desired properties, including filtration, centrifugation, precipitation, or chromatographic techniques. Subsequently, the purified biopolymers are dried and formulated into various forms such as powders, films, or fibers, tailored to their intended applications (50, 52). Figure 3 illustrates the synthesis of biopolymers from algal biomass. The cost affordability of biopolymers derived from micro and macroalgae depends on several factors. These include the expense of algae cultivation, harvesting, and pre-treatment, which can vary based on production scale and algae farm location. Moreover, the choice of extraction method impacts costs, as certain techniques may necessitate costly equipment or consumables. Nevertheless, it is essential to note that the cost of biopolymers from algae has decreased over time due to advances in extraction technologies, improved cultivation practices, and economies of scale.

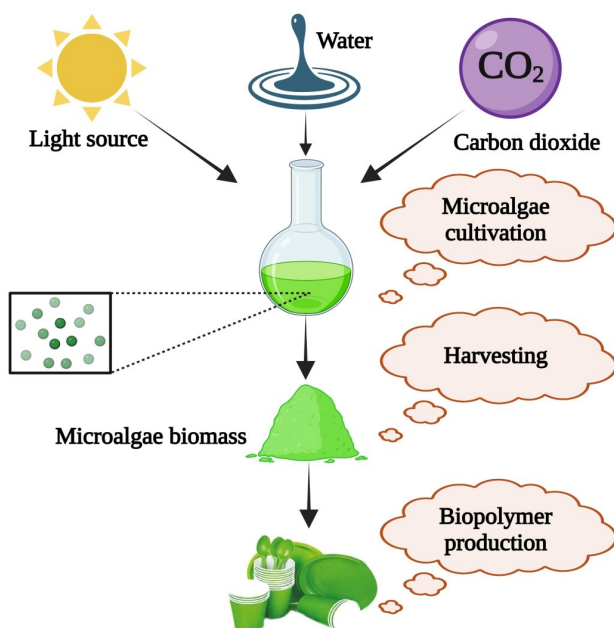


Fig. 3. Synthesis of Algal Biopolymers

Furthermore, the abundance of algae resources worldwide renders them a potentially cost-effective feedstock for biopolymer production. As technology continues to advance, the cost affordability of biopolymers from micro and macroalgae is expected to further improve, establishing them as a viable alternative to conventional polymers.

Microalgal Biopolymer and its Utilization in Industry

Microalgae hold significant implications far beyond their current research applications, particularly in the industrial sector (as depicted in Table 2). In recent years, there has been rapid growth in the utilization of microalgae, garnering attention due to their ability to produce high-value products, making them a promising substitute for finite resources like petroleum, plastics, and polymers. The increasing reliance on non-renewable resources, such as fossil fuels (coal, petroleum, and oil), has raised environmental concerns. Consequently, there is a growing need to explore novel alternatives to generate renewable and biodegradable resources (21, 53, 54). The plastic industry, which produces over 300 million tons of petroleum-derived plastics annually, plays a vital role in the global economy. However, the slow degradation rate of plastics, taking up to 100 years on average, poses a significant environmental hazard, contributing to the generation of hazardous waste (55). Microalgae's abundant natural compounds and their simple and rapid growth characteristics make them a promising candidate for replacing non-biodegradable petroleum-derived plastics (21). Fig. 4 illustrates various applications of biopolymers derived from microalgae, highlighting their potential in addressing the environmental challenges posed by conventional plastics.

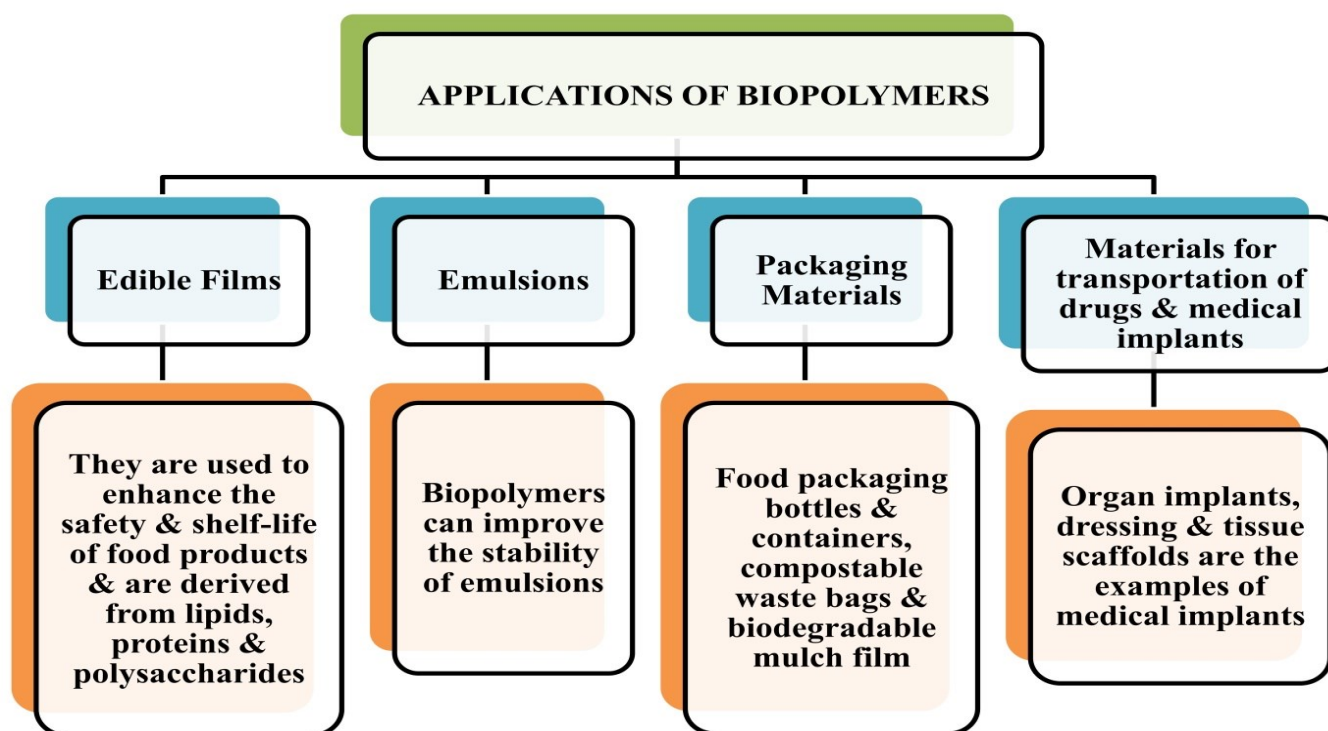
Use of microalgae in food industry

By 2050, the world's population is projected to reach 10 billion, necessitating a 70% increase in food production to sustain an additional 2.3 billion people (56). Meeting such a substantial demand for food requires exploring innovative sources of nutrition, especially those that can be cultivated without the need for arable land. One promising candidate is microalgae, often referred to as "the food of the future" because of its ability to provide nutrient-rich food and serve as livestock feed (57). One of the most significant advantages of microalgae is that they do not require arable land or fresh water for cultivation, presenting a promising solution to the problem of food scarcity.

Microalgae, known for their rapid growth, have garnered attention as a potential source for producing biopolymers and bioplastics, particularly for food packaging materials (58, 59). The microalgal-based polymers offer several advantages in the food industry due to their ease of production and renewable origin (59). Additionally, microalgae contain beneficial components such as proteins, vitamins, carbohydrates, essential minerals, and polyunsaturated fatty acids, making them valuable for health supplements (60, 61). Studies focusing on microalgae like *Arthrospira platensis* and *Chlorella vulgaris* have supported their potential as nutraceuticals

Table 2. Microalgae based biopolymer application in different industries.

Microalgae	Biopolymer	Applications	Reference
<i>Arthrospira platensis</i>	polyhydroxybutyrate (PHB)	Production of biofunctionalized nanofibres	(76)
<i>Calothrix scytonemica</i>	Polyhydroxyalkanoate (PHA)	Production of bioplastic material used to cast thin and brittle plastic film.	(25)
<i>Calothrix scytonemica</i> TISTR 8095	polyhydroxybutyrate	Conversion of solar energy into PHB (In a bioenergy form)	(77)
<i>Chlorella vulgaris</i>	Polyhydroxyalkanoates (PHB)	Production of biodiesel	(29)
<i>Chlorogloea fritschii</i>	poly-3-hydroxybutyrate	Production of bioplastics	(78)
<i>Nostoc muscorum</i>	Polyhydroxyalkanoates (PHB)	Replacement of petrochemical source of polymers	(30)
<i>Spirulina</i> sp.	starch	food industry	(79)
<i>Eustigmatophyte nannochloropsis</i> sp.	starch	Feedstock of biofuel and biodiesel production	(80)

**Fig. 4.** Different Usage of Biopolymer

(62). Other microalgae species, including *Dunaliella salina*, *Haematococcus pluvialis*, and *Phaeodactylum tricornutum*, are rich in antioxidants and find applications in cosmetics and the food industry. Microalgae have been found to synthesize very long-chain polyunsaturated fatty acids (VLC-PUFAs) belonging to the omega-6 and omega-3 families, making them suitable for use as food supplements (63). Moreover, major pigments present in microalgae, such as phycocyanin, lycopene, astaxanthin, prodigiosin, canthaxanthin, violacein, beta-carotene, melanin, and riboflavin, are used as food colorants (64). One study focused on the green algae *Chlamydomonas reinhardtii* and investigated its response to cold stress, evaluating the production of compounds under different temperature conditions. The findings revealed that temperatures ranging from 10 to 20°C induced the accumulation of carotenoids and chlorophyll content in *C. reinhardtii*. This suggests the algae's ability to acclimate to cold stress and indicates that lowering temperatures can effectively enhance pigment production in this species (65).

Use of microalgae in pharmaceutical industry

Microalgae have gained significant attention in biotechnology for their ability to produce valuable biocompounds, such as biodegradable biopolymers. These biopolymers exhibit properties similar to conventional polymers but offer enhanced biocompatibility, making them particularly suitable for medical applications, including the manufacturing of artificial limbs and suture materials. In the pharmaceutical industry, a biopolymer called poly-3-hydroxybutyrate (PHB), derived from *Spirulina* biomass, is utilized for nanoencapsulation of active ingredients. This process creates a protective barrier around the active substances, preventing foreign substances from interfering with their efficacy (66). Recently, researchers have been focusing on utilizing extracellular polymeric substances (EPS) in the fabrication of microorganisms, which holds promise in bioremediation applications. The pharmaceutical potential of microalgae has piqued interest in large-scale production of EPS from green microalgae (67, 68). Exploration of red microalgae EPS, specifically from the

Porphyridium genus, has revealed its properties as an extracellular polymeric substance with extensive biomedical applications. These applications include antimicrobial, hydrating, antioxidant, and anti-inflammatory properties (69). The broad spectrum of uses makes red microalgae EPS a promising candidate for various biomedical applications.

Future Perspectives

The escalating global production of plastic waste has led to widespread plastic pollution, necessitating urgent and innovative measures to mitigate its environmental impact. Ecosystems and marine life have been severely affected by the widespread demand for plastic products. As a greener alternative, bioplastics have gained popularity due to their sustainable nature, low carbon footprint, low toxicity, and high degradability. Among the various sources for producing biopolymers, bio-based polymers derived from microorganisms, plants, animals, agricultural waste, and other biological resources have emerged as promising substitutes for traditional plastics. Notably, microalgae present a unique and promising opportunity for bioplastic synthesis and warrant further exploration and enhancement. The concept of a feasible biorefinery perspective for utilizing microalgae biomass in biopolymer production offers significant advantages and calls for additional investigation. Specifically, the focus should shift from single-species cultivation to multi-species systems, which can significantly boost polymer productivity. Moreover, there is a pressing need for intensified research efforts to bioprospect novel microalgal strains and develop efficient methods for screening, producing, and extracting biopolymers. By delving deeper into these areas, we can unlock the full potential of microalgae-based bioplastics and contribute to reducing plastic pollution on a global scale. In the forthcoming years, it is crucial to focus on mapping polymer production from diverse microalgae species and employing innovative and combined cultivation techniques to enhance yield while reducing costs (47). Additionally, the perception of customers plays a pivotal role in promoting the adoption of algal-based biopolymers. Therefore, effective marketing strategies should emphasize the advantages of a circular economy, biodegradability, and the cost-effectiveness of algae-based biopolymers to foster a positive societal mindset (14). Among the microalgae species used for biopolymer synthesis, *Chlorella* and *Spirulina* stand out as the most popular choices. Furthermore, microalgae such as *Synechococcus subsalsus*, *Calothrix sp.*, *Oscillatoria sp.*, *Spirulina sp.*, *Synechocystis sp.*, and *Nostoc muscorum* have demonstrated the ability to produce significant quantities of polyhydroxyalkanoates (PHAs) and their derivatives without competing for arable land. However, to ensure widespread adoption of bioplastic products derived from microalgae in the market, economic viability at an industrial scale must be addressed. This necessitates further development of bioplastic manufacturing techniques from microalgae.

Conclusion

The extensive use of petroleum-based plastics has become a significant environmental and societal concern. To address these issues, there is a critical need to develop eco-friendly and sustainable bioplastics suitable for various industrial sectors such as medical, food, cosmetics, and nutraceuticals. Among the potential solutions, algal-based biopolymers have emerged as a promising path towards achieving a circular bioeconomy. Algal biomass holds tremendous potential for replacing petroleum-based and synthetic plastic materials due to several advantages. Notably, algae exhibit a rapid growth rate, require minimal nutrients, do not necessitate large arable land, and have a high CO₂ fixation rate. These attributes make them an attractive raw material for biopolymer production. However, the production process faces several challenges that need to be addressed. The biochemical pathways involved in algal biopolymer production remain incompletely understood. Additionally, extraction methods, identification of suitable algal species, and optimization of cultivation conditions are crucial factors for the successful application and commercialization of algal-based biopolymers. Nonetheless, it is evident that algae offer promising potential as a renewable source for producing biopolymers, which can significantly contribute to the realization of a circular bioeconomy. Efforts to overcome the current bottlenecks and further research into the intricacies of algal biopolymer production will undoubtedly pave the way for more sustainable and environmentally friendly alternatives to conventional plastics.

Acknowledgements

This paper has been supported by the grant provided by DST, Govt. of India under the project (DST/INT/RUS/RSF/P-60/2021). This paper also supported by RUDN University Strategic Academic Leadership Program.

Authors' contributions

RD carried out the conceptualization, data curation and writing – original draft. SM carried out the conceptualization, data curation and writing – original draft. SS carried out the writing – review & editing. NCJ carried out the writing – review & editing. PB carried out the writing – review & editing. RS carried out the data curation and writing – original draft. VK carried out the conceptualization and supervision. PG carried out the conceptualization and supervision.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None.

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