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Biopolymers Production Strategies and Their Usage as Clean Material for Environmental Remediation

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ABSTRACT

The renewable sources, biodegradability, and customizable physicochemical features of biopolymers make them viable alternatives to synthetic materials. Their use in wastewater, air, and soil remediation offers promising answers to pollution problems. This comprehensive analysis encompasses the natural extraction, microbial biosynthesis, and chemical polymerization of biopolymers. Chitosan, alginate, bacterial cellulose, and polyhydroxyalkanoates (PHAs) are excellent biopolymers for wastewater treatment because they effectively adsorb heavy metals, dyes, and organic contaminants. Additionally, biopolymer-based membranes, composites, and hydrogels are garnering attention for air filtration and soil stabilization. Functional modifications have enhanced the efficiency and environmental sustainability of biopolymers through the application of synthetic biology and nanotechnology. This paper explores the potential of biopolymer-based environmental remediation technologies to replace synthetic materials in sustainable pollution management, highlighting recent advances, challenges, and prospects.

INTRODUCTION

The escalating environmental burden from non-biodegradable synthetic polymers, derived primarily from fossil fuels, has become a significant global concern because of their persistence, toxicity, and contribution to pollution in water, soil, and air. These materials not only deplete non-renewable resources but also generate long-lasting waste that threatens ecosystems and human health (Kibria et al. 2023, Islam et al. 2024). In response, biopolymers have garnered increasing attention as a sustainable alternative. Derived from renewable sources and often biodegradable, biopolymers offer promising advantages in environmental compatibility, resource efficiency, and functional versatility. This review examines recent strategies in biopolymer production and their emerging applications in environmental remediation, highlighting how these natural and engineered materials can effectively replace synthetic polymers to mitigate pollution and support a circular bioeconomy (Samir et al. 2022, Edo et al. 2025).

Biopolymers play a vital role by competing with non-biodegradable synthetic polymers, offering unique advantages such as eco-friendliness and high biodegradability. Moreover, they can be biosynthesized from various biological resources. Biopolymers possess significant market potential due to their extensive range of applications. Biopolymers are found in multiple sources, including microbial and animal origins, and most are obtained from agricultural waste. Lignocellulosic-based agricultural residues are gaining market traction from

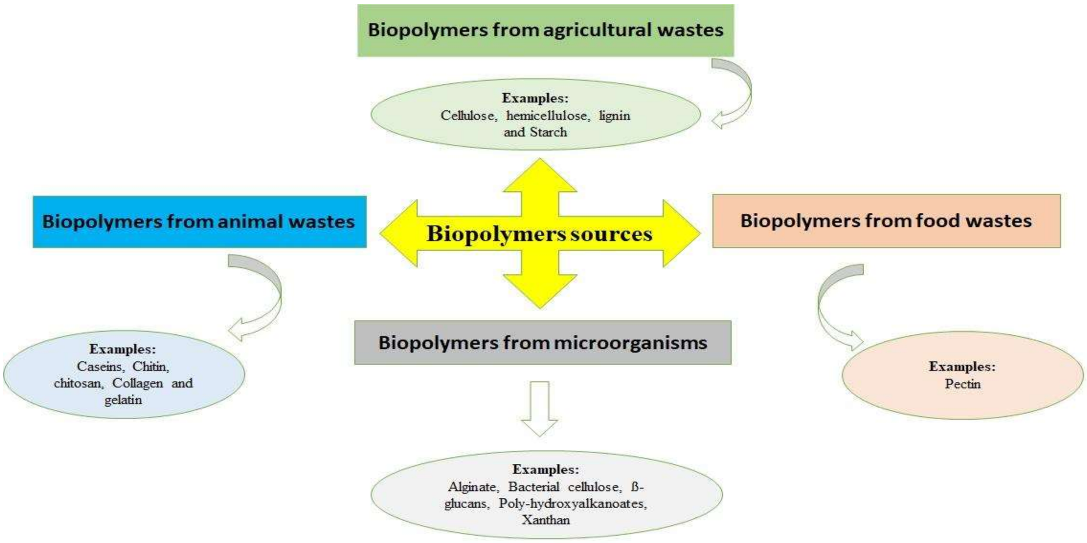

Fig 1: Biopolymers sources.

Table 1: Biopolymer origin, synthesis, and sources.

Biopolymer origin	Types	Examples	Sources
Biomass	1. Polysaccharides	Starch, cellulose, chitosan, alginate, carrageenan, pectin, and gums or their derivatives.	wild or genetically modified microorganisms
	2. Proteins	Gelatin, casein, whey, and collagen	Animal and plant origin
	3. Lipids	Waxes	Beeswax and carnauba wax
Synthesized from bioderived monomers		Polylactic acids (PLA)	Renewable agro-wastes
Bioderived monomers	-	Poly(hydroxyalkanoate)s (PHAs), poly(hydroxybutyrate)s (PHBs), bacterial cellulose, xanthan, gellan, pullulan.	Wild or genetically modified microorganisms

agricultural wastes due to their substantial global production (Rai et al. 2021, Iqbal et al. 2025). Biopolymers are defined as large molecules synthesized by microbial, plant, and animal cells, composed of highly repetitive chemical units. Fig. 1 illustrates various natural sources of biopolymers, along with examples.

The biochemical composition of biopolymers primarily comprises polysaccharides (cellulose, starch, chitosan, chitin, alginic acid, hyaluronic acid, and pectin), proteins (collagen, elastin, albumin, fibrin, gluten, and soy proteins), and nucleic acids (DNA and RNA), with primary sources derived from plant, animal, and microbial origins. Investigating the physical, chemical, biological, and mechanical properties of biopolymers enables their application in various industries, including food, pharmaceuticals, medicine, and environmental sectors (Hassan et al. 2019). Biopolymers synthesized through natural processes, including bioplastics, pullulan, dextran, xanthan, bacterial cellulose, microbial exopolysaccharides, and capsular polysaccharides, are widely utilized in medical, agricultural, agro-industrial, packaging, and environmental applications (Francis et al. 2013, Chaabouni et al. 2014, Manubolu et al. 2024, Lad et al. 2024). Based on the literature and data, biopolymer production methods include extraction from agricultural waste and animal sources, as well as synthesis via classical chemical methods (e.g., polylactic acid, PLA). Additionally, polymers are produced from indigenous and genetically modified microorganisms. Table 1 shows various biopolymer production strategies. According to the literature, technical advancements in synthesizing biopolymers from natural sources and bioderived feedstocks have been noted (Volf and Popa 2018, Chen et al. 2019, George et al. 2020).

NATURAL BIO-BASED POLYMERS CAN BE HARNESSED WITH PARTIAL MODIFICATION AS AN EFFECTIVE PRODUCTION STRATEGY

In recent years, bio-based polymers have seen a surge in demand for their versatile applications. Primarily, modification of functional groups and their properties is sought in recent technical advancements to meet our industrial applications (Das et al. 2024). Table 1 presents three significant types of biopolymers, along with their origins and sources.

Functionality of Biopolymer

The production of biopolymers from renewable biomass has become one of the most widely adopted sustainable alternatives to fossil-fuel-based synthetic polymers. Unlike traditional plastic synthesis, which relies on nonrenewable petrochemicals and generates persistent waste, biopolymers are often biodegradable, non-toxic, and derived from abundant natural resources. This shift aligns with growing environmental regulations and rising consumer demand for eco-friendly materials (Pinaeva & Noskov 2024, Jha et al. 2024).

Among the most promising strategies in recent years is the cell factory approach, in which microorganisms are genetically engineered to convert simple carbon sources—typically glucose, glycerol, or lignocellulosic hydrolysates-into high-value polymer precursors. Glucose, in particular, is favored for its low cost, wide availability, and compatibility with many microbial systems. Through in vivo chemical synthesis and metabolic engineering, researchers have significantly advanced the microbial biosynthesis of various biopolymer building blocks (Mitra et al. 2020, de Souza & Gupta 2024).

Over the past three decades, several notable milestones have been achieved in this field:

Glucaric acid: Produced using engineered E. coli strains (Moon et al. 2009), glucaric acid is a precursor to biodegradable polyesters and has potential applications in detergents, hydrogels, and biomedical devices. Its production exemplifies how central metabolism can be rerouted to yield value-added products from glucose.

Putrescine: This diamine, synthesized by Corynebacterium glutamicum and E. coli (Qian et al. 2009), serves as a monomer for nylon-4,6, a biodegradable polyamide. Biosynthetic production of putrescine replaces the energy-intensive petrochemical routes typically required for polyamide synthesis.

3-Hydroxybutyrate (3HB): A key monomer in the synthesis of polyhydroxybutyrate (PHB), 3HB is produced by various bacteria, including Ralstonia eutropha (Jung et al. 2010). PHB exhibits thermoplastic properties similar to polypropylene, making it a potential substitute for petroleum-derived plastics in packaging and agriculture.

1,4-Butanediol (BDO): Traditionally produced via petrochemical synthesis, BDO is now biosynthesized by engineered microbes, including E. coli and Clostridium species (Oliver et al. 2013, Kumar et al. 2020). BDO is a versatile precursor to biodegradable plastics, including polybutylene succinate (PBS) and polybutylene terephthalate (PBT).

These advances underscore not only the functional versatility of biopolymers but also the potential for modular customization, enabling the design of polymers with specific mechanical, thermal, or chemical properties tailored to diverse applications, including biomedicine, agriculture, packaging, textiles, and electronics. Significantly, the functionality of biopolymers is determined not only by their monomeric composition but also by molecular weight, branching, crystallinity, and interactions with other molecules. Advances in synthetic biology and protein engineering now enable researchers to fine-tune these properties by modifying biosynthetic enzymes or incorporating non-natural building blocks into the polymer backbone (Arif et al. 2022, Khalil et al. 2025).

Despite these successes, current biosynthetic approaches face several technical limitations. Low titers and yields in industrial-scale fermentation, high recovery and purification costs, limited host tolerance to toxic intermediates, and substrate competition within central metabolism all constrain growth and productivity. To overcome these challenges, efforts are directed toward optimizing host strains, developing co-culture systems, and integrating dynamic pathway regulation to balance growth and production. Furthermore, combining metabolic engineering with process innovations such as continuous fermentation or in situ product recovery is expected to enhance overall efficiency and reduce costs. The functionality of biopolymers derived from biomass not only fulfills sustainability goals but also offers a broad spectrum of application-specific properties. Continued innovation in microbial engineering and bioprocess design will be essential for translating these materials into scalable, commercially viable solutions (de Souza & Gupta 2024, Del Hierro et al. 2024).

Synthetic Biology as a Tool to Modify Biopolymers

Synthetic biology has emerged as a transformative tool for modifying and producing biopolymers with enhanced efficiency, precision, and sustainability. Traditional one-step microbial production of polymers, while promising, often suffers from low yields, slow growth rates, and inefficient substrate conversion, particularly with wild-type or unoptimized strains. Moreover, these processes typically rely on chemical catalysts and harsh solvents for polymer extraction and purification, increasing environmental and economic burdens (Anderson et al. 2018, Kaur et al. 2024).

Commonly produced biopolymers include chitin, alginate, polylactic acid (PLA), and polyhydroxyalkanoates

(PHAs). For instance, chitin, extracted primarily from crustacean shells, is limited by its animal origin, raising sustainability and allergenicity concerns. Similarly, alginate, derived from brown algae, faces challenges due to seasonal availability and batch variability, which can affect product consistency. PHAs and PLA, although microbial in origin, often require complex feedstocks and multiple downstream purification steps because of mixed metabolic byproduct accumulation (Sharma et al. 2024, Kaur et al. 2024).

A key limitation of conventional metabolic engineering is the difficulty in controlling pathway fluxes, which can lead to unintended accumulation of intermediates or metabolic burden that compromises cell growth. Additionally, the limited range of naturally occurring monomers restricts the mechanical and functional diversity of biopolymers, limiting their potential applications. Synthetic biology addresses these challenges by enabling fine-tuned control of gene expression, modular pathway design, and the incorporation of non-natural monomers (Aravind et al. 2015, 2016, Arif et al. 2024). For example, engineered strains of E. coli have been developed to produce cellulose nanofibers with customized lengths and crystallinity. At the same time, synthetic pathways in Cupriavidus necator have been used to create novel polyhydroxyalkanoates (PHAs) with side chains that confer elasticity and biodegradability. These modifications not only enhance the functional properties of the polymers but also streamline production by eliminating unnecessary enzymatic steps (Zhang et al. 2022).

CRISPR-based genome editing and biosensor-guided pathway optimization have enabled dynamic regulation of biosynthetic pathways, allowing microbial systems to adjust in real time to fluctuations in precursor availability or metabolic stress. This results in more robust production systems that are resilient under industrial fermentation conditions (Xin et al. 2025). However, challenges remain. Many engineered strains still face scale-up issues, including instability of synthetic pathways during prolonged fermentations and sensitivity to industrial stressors, including pH and shear forces. Moreover, regulatory and safety concerns around the use of genetically modified organisms (GMOs) in open environments or consumer products may slow the commercial deployment of such technologies. Despite these limitations, the integration of synthetic biology with computational modeling, machine learning, and high-throughput screening holds promise to accelerate the development of next-generation biopolymers. These polymers can be fully bio-based, biodegradable,

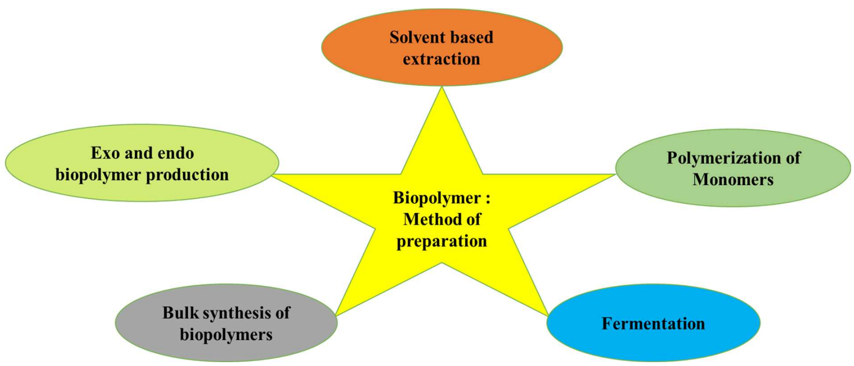

Fig. 2: Method of preparation of biopolymers.

Table 2: Overview of the biopolymer synthesis pathway.

Direction of polymer synthesis	Glucose	Glucose	Glucose	Glucose
↓	Glucose 6-phosphate	Glucose 6-phosphate	Acetyl coenzyme A	Glucose 6-phosphate
	Glucose 1-phosphate	Glucose 1-phosphate	Oxaloacetate	Fructose 6-phosphate
	Glucuronic acid - glucose	Glucuronic acid - glucose	Fructose 6-phosphate	Glucosamine 6-phosphate
	Cellulose	N-acetylglucosamine 1-phosphate	Mannose 6-phosphate,	N-acetylglucosamine 6-phosphate
		UDP-N-acetylglucosamine	Mannose 1-phosphate	N-acetylglucosamine 1-phosphate
		Hyaluronan	GDP-mannose	UDP-N-acetylglucosamine
			GDP-mannuronic acid	Chitin
			Alginate	Chitosan

and tailored for specific applications (Palladino et al. 2024).

PRODUCING BIO-BASED MONOMERS BY FERMENTATION AND/OR VIA CONVENTIONAL CHEMISTRY FOLLOWED BY POLYMERIZATION

Method of Preparation

Biopolymers possess excellent biological and biodegradable properties, but they lack specific mechanical properties, including low chemical resistance, limited processing capacity, and short storage duration. Various methods can be implemented to achieve maximum yield while retaining the properties of biopolymers and overcoming challenges (Pinaeva & Noskov 2024). Fig. 2 illustrates various methods for preparing biopolymers.

Fermentation: This method utilized bacteria, fungi, and algal species to produce specific types or different groups of biopolymers, which were produced using specific substrates as the sole carbon source (Chang et al. 2015). Major biopolymers (Alginate, bacterial cellulose, dextran, Hyaluronic acid, etc.) use glucose and/or sucrose as primary substrates. Very few groups of polymers (Gellan and pullulan) are produced using industrial waste as substrate. Table 3 provides detailed information on the types of polymers, substrates used for Fermentation, and polymer-producing microorganisms.

Polymerization: The monomeric form of polymers is highly prepared for the synthesis of microstructures. In this method, the polymerization of monomers occurs in a series of sequential reactions, with each step representing the functionalities of the monomers and their steric effects. For example, in the formation of alkene units, more straightforward steps are required, whereas carbonyl groups necessitate more complex steps. In the presence of strong acids, alkane units are polymerized (Doyle et al. 2010). Similarly, the production of Polycaprolactone (PCL) by two methods, which include 1. polycondensation of hydroxycarboxylic acid and 2. ring-opening polymerization of ε-caprolactone (Udayakumar et al. 2020). Table 2 provides an overview of the biopolymer synthesis pathway.

Solvent-based extraction: In solvent-based extraction, the process is governed by mechanical operations, including sifting, filtration, and centrifugation of biomass for biopolymer extraction (Faidi et al. 2019). To improve efficacy, biopolymers were extracted from pretreated biomass using various solvents (Mahmood and Moniruzzaman, 2019). Similarly, to mitigate solvent toxicity, green solvents such as ionic liquids, deep eutectic solvents, bio-derived solvents, non-halogenated solvents, and accelerated solvent systems have been used to extract polymers from biomass (Gu and Jérôme, 2013).

Endo and exo biopolymer production: Endo polymers, such as polyhydroxyoctanoate (PHO), possess unique characteristics and low melting temperatures, enabling the formation of lightweight composites (Van de Velde & Kiekens 2002, Ujang et al. 2009). These polymers are produced intracellularly by eubacteria. Similarly, Ganoderma applanatum, Collybia confluens, and Pleurotus eryngii were identified as potential sources of endopolymer. These fungi can be cultivated using Mushroom Complete Medium (MCM) (Yang et al. 2007, Jeong et al. 2008, Moradali & Rehm 2020). In exopolymer production, submerged cultures of fungal species have been widely employed, and parameters such as carbon and nitrogen sources, pH, temperature, and agitation have been standardized to optimize exopolymer production from fungal mycelia. For example, Paecilomyces japonica was used to optimize the production of maximal dry-weight biomass for extracting exopolymers (Bae et al. 2000). Similarly, Paecilomyces tenuipes C240 was studied to optimize factors using a One-Factor-at-a-Time Approach and an orthogonal matrix (Xu et al. 2003). Besides fungi, Ganoderma lucidum mushrooms and Phellinus linteus KCTC 6190 were studied to optimize mycelial growth. Similarly, Mushroom Complete Medium (MCM), Yeast Malt (YM), and Potato Malt Peptone (PMP) were studied to standardize exo-biopolymer production. PMP medium was the best medium for maximal polymer production (Kim et al. 2002). For a comparative study, Cordyceps militaris exhibited maximal mycelial growth at 7.5 days and maximal exopolysaccharide formation at 9.5 days (Park et al. 2001).

Bulk synthesis: Biopolymers are extracted and synthesized from various sources, including microbes, plants, and renewable natural sources such as food and animal waste (Kaplan 1998). Extraction methods vary by source. Biopolymers are generally produced under submerged conditions in fed-batch mode. For example, PHB was synthesized by optimizing carbon and nitrogen sources using reactor-fed bacteria of the species Ralstonia eutropha. Optimal biopolymer production depends on factors such as pH, substrate concentration, retention time, and substrate feeding rate. Similarly, genetic algorithms for fed-batch cultivation have been studied using nutrient feeding rates and dilution rates to maximize PHB production (Khanna & Srivastava 2005, Lai et al. 2013, Stanley et al. 2018).

PRODUCING BIO-BASED POLYMERS DIRECTLY VIA MICROORGANISMS

Alginate

Alginates are water-soluble, linear, anionic heteropolysaccharides. They are distributed in the cell walls of algae in the family Phaeophyceae, which include *Laminaria*

Table 3: Substrate and biopolymer-producing microorganisms.

Sl. No.	Type of Biopolymers	Producing microorganism	Substrate used	References
1.	Alginate	*Pseudomonas* and *Azotobacter* spp. (mostly *A. vinelandii*)	Sucrose	(Valentine et al. 2020, Dudun et al. 2021)
2.	Bacterial cellulose	*Gluconacetobacter, Agrobacterium, Aerobacter, Achromobacter, Azotobacter, Escherichia, Rhizobium, Sarcina,* and *Salmonella* sp.	Glucose and sucrose	(Chawla et al. 2009, Almihyawi et al. 2024, Mishra et al. 2022)
3.	Cyanophycin	*Cyanobacteria, Acinetobacter* spp., *Bordetella* spp., and *Desulfitobacterium hafniense*	Arginine and protein hydrolysate	(Solaiman et al. 2011, Aravind et al. 2016, Zou et al. 2022)
4.	Dextran	*Leuconostoc, Streptococcus, Lactobacillus* sp., *L. mesenteroides, Gluconobacter* sp., and *Pediococcus pentosaceus*	Sucrose and maltodextrins	(Patel et al. 2010, Wang et al. 2023, Baek et al. 2025)
5.	Gellan	*Pseudomonas elodea* and *Sphingomonas* spp., *S. paucimobilis*	Industrial waste products	(Fialho et al. 2008, Sá-Correia et al. 2002, Wu et al. 2011)
6.	Hyaluronic acid	*Streptococcus zooepidemicus, S. equi,* and *Pasteurella multocida*	Glucose, amino acids, nucleotides, salts, trace elements, and vitamins	(Kogan et al. 2007, Zakeri et al. 2017, Shikina et al. 2022)
7.	PHAs	*Cupriavidus necator* and *Phaeodactylum tricornutum*	Starch, alcohol, and industrial waste products	(Koller et al. 2010, Morlino et al. 2023)
8.	Poly-ε-lysine	*Streptomyces albulus*	Glucose	(Hamano et al. 2011)
9.	Pullulan	*Aureobasidium pullulans, Tremellales enterica, Cytaria* sp., *Cryphonectria parasitica,* and *Rhodotorula*	Industrial waste products	(Singh et al. 2008, Cruz-Santos et al. 2023, West, 2022)
10.	Xanthan gum	*Xanthomonas campestris*	Glucose and sucrose	(Palaniraj et al. 2011)

hyperborea, Macrocystis pyrifera, Laminaria digitata, and *Ascophyllum nodosum*. Besides algae, many bacterial species, such as *Pseudomonas* and *Azotobacter*, also produce alginate-like polymeric materials (Sabra & Deckwer 2005, Abka-Khajouei et al. 2022).

Dextran

Dextrans are hydrophilic polysaccharides produced by species like *Leuconostoc mesenteroides* and *Streptococcus mutans*. It has α (1-6)-linked glucan side chains attached to the 3-positions of the glucose units, forming the backbone. Class 1 - α (1 → 6)-linked d-glucopyranosyl backbone modified with side chains of d-glucose branches with α (1 → 2), α (1 → 3), and α (1 → 4)-linkage, class 2 - a backbone structure of alternating α (1 → 3) and α (1 → 6)-linked d-glucopyranosyl units with α (1 → 3)-linked branches, whereas class 3 - a backbone structure of consecutive α (1 → 3)-linked d-glucopyranosyl units with α (1 → 6)-linked branches. Dextran's physical and chemical properties generally vary depending on the source and production methodologies (Saboktakin et al. 2010, Díaz-Montes 2021).

Xanthan

Xanthan is a β-(1, 4)-linked heteropolymer composed of pentasaccharide units found in *Xanthomonas* species. This polysaccharide is widely used in food products as a thickening and gelling agent (Rehm 2010, Martínez-Burgos et al. 2024)

Gellan

Gellan is a heteropolymer widely extracted from *Sphingomonas* species and is a β-(1, 3)-linked, containing tetrasaccharide units (West 2021).

Curdlan

Curdlan, a β-(1,3)-linked homopolymer, is isolated chiefly from a few species, including *Agrobacterium, Rhizobium*, and *Cellulomonas* (Al-Rmedh et al. 2023).

Polyhydroxyalkanoates (PHA)

PHA is a unique and ideal example of intracellular biopolymers, mainly produced by many bacterial species. It contains β-hydroxy fatty acids, where the R group ranges from methyl to tridecyl. In particular, the main biopolymer is PHB (polyhydroxybutyrate), a prominent member of the PHA family. In addition, many copolymers are synthesized, including PHB family members such as poly (hydroxybutyrate-co-hydroxyvalerate) (PHBV), poly (hydroxybutyrate-co-hydroxyhexanoate) (PHBH), and poly (hydroxybutyrate-co-hydroxyoctanoate) (PHBO) (Vicente et al. 2023).

Cyanophycin

Cyanophycin is a polyamide most widely extracted from cyanobacteria. Biochemically, it consists of a repeating heteropolymer composed of dipeptide units of aspartate and arginine. Cyanophycin is commonly used as a water softener and dispersant (Markus et al. 2023).

ε-poly-l-lysine

ε-poly-L-lysine is a polyamide, similar to cyanophycin, and is widely found in the bacterial species *Streptomyces albulus*. It is a homopolymer; lysine is one of the main amino acids present in this polymer. In the food industry, ε-poly-L-lysine is used as a food preservative and adsorbent (Pan et al. 2019).

PRODUCING BIO-BASED POLYMERS VIA ALGAE

Biopolymers are produced from algae in 3 ways: algal Fermentation, algal cell factories, and adding additives to algal biomass. In Fermentation, algal enzymes produce biopolymers from algal biomass (Khan et al. 2018). Fig. 3 shows three ways to produce biobased polymers from algae.

Algae undergo photosynthesis, producing essential nutrients that are used to synthesize biopolymers (Costa et al. 2018). Compression of algae and additives is the most common method used to prepare biocomposites (Ciapponi et al. 2019). Biopolymers such as Alginate, PHA, PHB, Carrageenan, Fucoidan, and κ-carrageenan from various algal sources were isolated using different methods, including solvent extraction, Microwave-assisted extraction, Ultrasound-assisted extraction, and Subcritical water extraction (Kartik et al. 2021). Yield (%) from these methods varies from source to source and extraction method. 4.50% of PHB was extracted from algal sources by using $CHCl_3$ with benzoic acid and MeOH with H_2SO_4 as solvent (Rueda et al. 2020), and 78.75% of κ-carrageenan was extracted from seaweed *Kappaphycus alvarezii* by using solvent 1-Butyl-3-methylimidazolium acetate by the Subcritical water extraction method (Gereniu et al. 2018).

By comparing all other biological sources, algae are one of the most promising sources for the production of biopolymers due to their scalability in production and the availability of biopolymer extraction strategies. Moreover, it can synthesize a wide range of bioproducts, including carbohydrates, lipids, pigments, polysaccharides, proteins, polymers, and other biocompounds. Due to their Low-cost production and sustainable nature, biopolymers from algae serve as the best model organism for producing various bioproducts (Khoo et al. 2019, Parsons et al. 2020, Lutzu et al. 2021). Table 4 summarises various biopolymers and biopolymers produced by algae.

Comparative Insight on the Scalability of Algal-Based Biopolymer Production Methods

Among the various approaches to producing biopolymers from algae, namely algal Fermentation, algal cell factories, and additive-assisted biomass processing, the most scalable method is continuous Fermentation using engineered algal strains in closed photobioreactors. This approach offers several key advantages: it enables precise control over growth conditions, maximizes biomass productivity, and supports

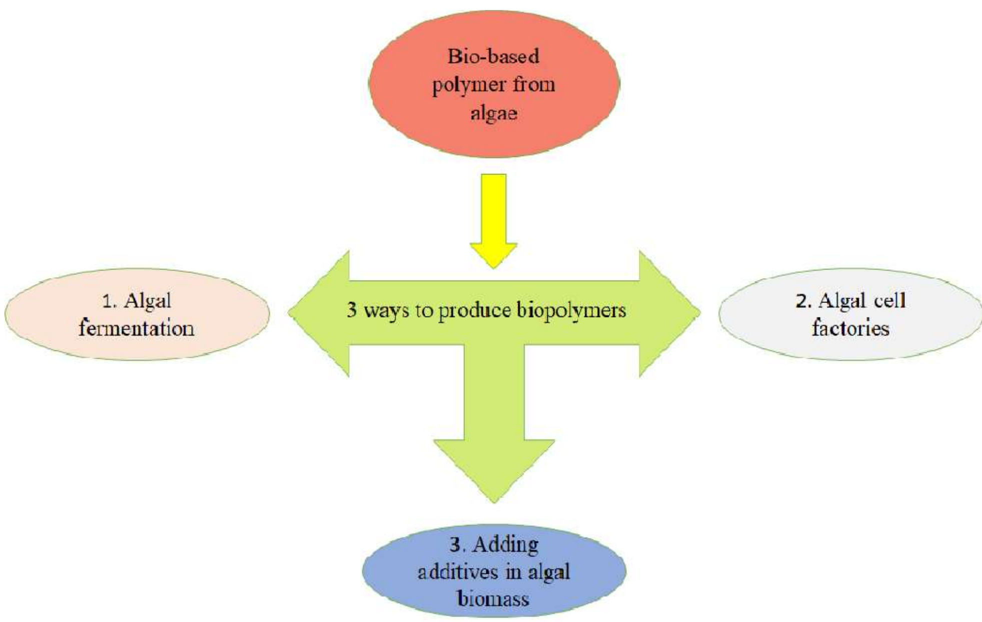

Fig. 3: Ways to produce bio-based polymers from algae.

the high-yield production of target biopolymers, such as polyhydroxyalkanoates (PHAs) and polyhydroxybutyrate (PHB). Genetic enhancements can further improve strain efficiency, substrate utilization, and tolerance to stress, making algal cell factories highly adaptable for industrial-scale applications. In contrast, direct enzyme-mediated or additive-based extraction from algal biomass is comparatively less scalable due to variability in biomass composition, dependence on seasonal availability, and batch-to-batch inconsistency (Gaur et al. 2024, Adetunji & Erasmus 2024).

Similarly, advanced extraction techniques, including microwave-assisted and solvent-based methods, offer higher purity and yield but are limited by high energy consumption, equipment costs, and environmental considerations-factors that challenge their economic viability at commercial scales. Therefore, while these techniques are valuable at laboratory and pilot levels, their transition to full industrial deployment is less straightforward. Overall, the use of genetically optimized algae in controlled bioreactor systems represents the most scalable and sustainable pathway for consistent, high-volume biopolymer production, particularly when integrated with downstream biorefinery processes (Gautam et al. 2024, Cannavacciuolo et al. 2024).

ENVIRONMENTAL REMEDIATION APPLICATIONS OF BIOPOLYMERS

Environmental pollution from industrialization, agricultural runoff, and urbanization has necessitated the search for sustainable remediation solutions. Conventional remediation strategies, such as synthetic chemical adsorbents, incineration, and physicochemical treatments, often result in secondary pollution, high costs, and energy-intensive processes. In contrast, biopolymer-based materials derived from renewable natural resources offer biodegradability, biocompatibility, non-toxicity, and efficiency in removing various contaminants (Awogbemi et al. 2023, Al-Hazmi et al. 2024).

Biopolymers, including chitosan, alginate, cellulose, starch, xanthan gum, and microbial exopolysaccharides, have significant potential for addressing water pollution, soil contamination, air purification, and hazardous waste management. These materials operate through diverse mechanisms, including adsorption, filtration, chemical binding, encapsulation, and microbial-assisted degradation. The following sections provide an in-depth exploration of their applications across various environmental remediation domains (Kaur et al. 2024, Al-Hazmi et al. 2024).

Biopolymer-Based Materials for Wastewater Treatment

Water pollution is among the most pressing global challenges, with sources including industrial effluents, agricultural runoff, and domestic wastewater. Biopolymers have attracted significant attention as effective and sustainable materials for treating contaminated water (Fakhri et al. 2023).

Adsorption of heavy metals and toxic ions: Heavy metals, including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As), are toxic pollutants that accumulate in the environment, posing serious health risks. Biopolymer-based adsorbents offer efficient, cost-effective, and environmentally friendly alternatives for heavy-metal removal (Verma et al. 2021).

Chitosan-Based Adsorbents: Chitosan, a deacetylated derivative of chitin, is widely studied for its amino ($-NH_2$) and hydroxyl (-OH) groups, which enable metal-ion chelation. Modified chitosan nanocomposites (e.g., chitosan-metal oxide hybrids, chitosan-carbon composites) enhance

Table 4: Biopolymer-producing algae.

Sl. No.	Biopolymer	Algal species	References
1.	Polyhydroxy alkanoates (PHA)	*Ulva* sp.	(Steinbruch et al. 2020)
2.	Polyhydroxy butyrate (PHB)	*Nostoc* sp.	(Morales-Jiménez et al. 2020)
3.	Polyhydroxy butyrate (PHB)	*Synechocystis* sp.	
4.	Polyhydroxy butyrate (PHB)	*Porphyridium purpureum*	
5.	Polyhydroxy butyrate (PHB)	*Chlorella* sp.	(Naresh Kumar et al. 2020)
6.	Polyhydroxy butyrate (PHB)	*Scenedesmus* sp.	
7.	Alginate	*Sargassum muticum*	(Flórez-Fernández et al. 2019)
8.	Fucoidan	*Nizamuddinia zanardinii*	(Alboofetileh et al. 2019)
9.	Fucoidan	*Saccharica japonica*	(Saravana et al. 2018)
10.	Carrageenan	*Mastocarpus stellatus*	(Ponthier et al. 2020)
11.	κ-carrageenan	*Kappaphycus alvarezii*	(Gereniu et al. 2018)

adsorption efficiency by increasing surface area and stability. Alginate-Based Adsorbents: Alginate, extracted from brown algae, contains carboxyl (-COO^-) groups that effectively bind heavy metals. Alginate-based hydrogels and beads have been used in continuous-flow systems for wastewater treatment (Siddiqui et al. 2025).

Cellulose and Starch Derivatives: Functionalized carboxymethyl cellulose (CMC) and starch-based bioadsorbents exhibit strong interactions with metal ions, providing an additional biodegradable option for water purification (Godiya et al. 2019). Chitosan's effectiveness largely stems from its abundant amino (–NH_2) and hydroxyl (–OH) groups, which facilitate strong chelation with metal ions. For example, recent work has demonstrated that modifying chitosan with poly(vinyl alcohol) and nano-silica can significantly enhance its Cr(VI) adsorption capacity. Additionally, studies have shown that chitosan-based adsorbents retain high efficiency across multiple adsorption-desorption cycles, highlighting their potential for cost-effective and long-term use in industrial wastewater treatment (Alkhaldi et al. 2024).

Alginate, derived from brown algae, contains carboxyl (–COO^-) groups that bind heavy metals effectively. Recent advances include Ca-alginate beads embedded with magnetic nanoparticles, which achieve high adsorption efficiency for Pb(II) ions and enable facile magnetic separation of treated water (Ayach et al. 2024). Furthermore, integrating alginate with chitosan to form interpenetrating polymer networks has improved mechanical stability and adsorption performance, making these hybrid materials promising for scalable water treatment systems (Sundararaman et al. 2024).

Cellulose derivatives, such as carboxymethyl cellulose (CMC), offer versatility due to their modifiable structures. Recent research indicates that grafting polyethylenimine onto CMC enhances its adsorption capacity for Cd(II) and Pb(II) ions by increasing the density of active binding sites (Ghanbari et al. 2024). Similarly, starch-based adsorbents functionalized with amine or thiol groups have produced nanocomposites with enhanced porous structures, resulting in improved removal efficiencies for Hg(II) and As(V) (Sahu et al. 2024).

Across these studies, kinetic analyses often show that adsorption on biopolymer-based materials follows pseudo-second-order kinetics, suggesting chemisorption as the dominant mechanism. The adsorption isotherms frequently conform to the Langmuir model, indicating monolayer adsorption on a homogeneous surface. These mechanistic insights are crucial for optimizing adsorbent performance in real-world applications (Sundararaman et al. 2024).

Modifying biopolymers, such as chitosan, alginate, cellulose, and starch derivatives, has enhanced their adsorption capacities and improved their operational stability in dynamic treatment environments. Their natural abundance, low cost, and biodegradability make them particularly attractive for sustainable wastewater treatment strategies. Integrating these advanced materials into continuous-flow systems enables effective remediation while reducing secondary pollution and overall treatment costs (Ghanbari & Zare 2024).

Removal of organic pollutants and dyes: Organic pollutants-including synthetic dyes, pharmaceuticals, and pesticides-are persistent contaminants in wastewater that pose serious environmental and health risks. Their chemical stability and resistance to degradation make them challenging to remove using conventional treatments. Biopolymers, due to their natural abundance, biodegradability, and tunable functional groups, have emerged as promising materials for the removal and degradation of these compounds (Negrete-Bolagay et al. 2021, Peramune et al. 2022, Manubolu et al. 2024).

Chitosan, a cationic biopolymer rich in amino (–NH_2) and hydroxyl (–OH) groups, exhibits a strong affinity toward anionic dyes such as methylene blue and malachite green, resulting from electrostatic attraction and hydrogen bonding. Chemical modifications or blending with other polymers can further enhance its performance to improve mechanical stability and adsorption capacity (Vijayasree & Manan 2023, Kurczewska 2022). Alginate, derived from brown algae and featuring carboxyl (–COO^-) groups, is effective for adsorbing cationic dyes such as rhodamine B. Recent studies on alginate-based hydrogels have shown that tuning the porosity and functional group density can lead to high removal efficiencies even in complex textile effluents (Wang et al. 2022, Dhanalekshmi et al. 2021).

Biopolymers can support semiconductor photocatalysts in degrading organic dyes under light irradiation. For example, TiO_2-chitosan composites combine the excellent adsorption properties of chitosan with the photocatalytic activity of TiO_2, resulting in enhanced degradation of dye molecules under visible light. Similarly, biopolymer-ZnO hybrids have been shown to stimulate the production of reactive oxygen species (ROS), which accelerate the degradation of complex organic dyes (Weon et al. 2023, Mendis et al. 2023).

Incorporating activated carbon into biopolymer matrices further improves dye removal by leveraging the high specific surface area and porosity of activated carbon. Combined with biopolymers such as chitosan, cellulose, or xanthan gum, the resulting composites exhibit enhanced dye adsorption kinetics and capacities. For instance, chitosan–activated carbon composites have been reported to rapidly adsorb methylene blue, making them suitable for treating textile wastewater (Rehman et al. 2023, Kolya et al. 2023, Annu et al. 2024).

Biopolymer-based membranes for water filtration: Biopolymer-based membranes and hydrogels have emerged as advanced solutions for water purification, combining sustainability with high filtration efficiency. Membranes fabricated from biopolymers such as chitosan and cellulose acetate exhibit high porosity, mechanical strength, and favorable surface charge properties. These features enable effective removal of bacteria, viruses, and suspended solids from water. Chitosan-based microfiltration (MF) membranes can achieve high rejection rates for microbial contaminants, while cellulose acetate ultrafiltration (UF) membranes offer robust performance in terms of flux and fouling resistance (Gough et al. 2021, Mamba et al. 2021, Fijoł et al. 2022).

Advances in membrane technology have led to the development of nanofiltration (NF) membranes by incorporating nanoparticles into the biopolymer matrix. Modified membranes, for example, chitosan–TiO_2 or cellulose–ZnO hybrids, enhance the separation of multivalent ions and organic contaminants, providing additional functionalities such as photocatalytic degradation of pollutants. These systems achieve higher selectivity and improved permeate quality, making them attractive for selective separation processes (Li et al. 2023, Spoială et al. 2021).

Biopolymer-based hydrogels, formed by cross-linking polymers such as chitosan, alginate, or cellulose, offer an alternative strategy for pollutant removal. Their highly tunable pore structures and responsiveness to environmental stimuli (e.g., pH and temperature) enable controlled adsorption and subsequent desorption of pollutants. This controlled release is particularly valuable for designing innovative water treatment systems that

Table 5: Biopolymers in Environmental Applications.

Biopolymer	Application	Target Pollutant	Efficiency/Capacity	Reference
Chitosan	Heavy Metal Adsorption	Multi-metal	99% removal	(Ashraf et al. 2024)
Alginate	Heavy Metal Adsorption	As, Pb, Zn	67.42%, 95.31%, and 93.96%	(Spoială et al. 2021)
Cellulose	Heavy Metal Adsorption	As, Hg, Pb	177.1, 110.2 and 234.2 mg/g	(Zhan et al. 2018)
Starch+ Cellulose	Heavy Metal Adsorption	Pb, Zn, Cu	66.66, 58.82, and 47.61 mg/g	(Anghel et al. 2019)
Xanthan Gum	Heavy Metal Adsorption	Cd, Cu, Pb, and Zn	16.0 mg/g, 8.5 mg/g, 38.3 mg/L, and 7.2 mg/L	(Ko et al. 2022)
Chitosan	Wastewater Treatment	Dyes, Heavy Metals	99% and 98%	(Ayach et al. 2024)
Alginate	Wastewater Treatment	Organic Pollutants	89.3% removal	(Marques-da-Silva et al. 2022)
PHA	Wastewater Treatment	Acid Orange 7	96.44% removal	(Chang et al. 2022)
Pectin	Wastewater Treatment	Suspended Solids	-	(Jha and Mishra 2024)
Chitosan	Air Filtration	PM2.5	99.5%	(Hao et al. 2022)
Cellulose	Air Filtration & VOC Removal	Dust, Allergens, Microbes	99%	(Lippi et al. 2022)
Gelatin	Air Filtration & VOC Removal	VOCs, Formaldehyde	95%	(Kadam et al. 2021)
Chitosan	Soil Remediation	Heavy Metals	99%	(Pal et al. 2021)
Alginate-hydrogel	Wastewater	Hydrocarbons	78.8%	(Farid et al. 2024)
Pectin functionalized metal-organic frameworks	Soil Remediation	Pesticides	99%	(Liang et al. 2022)
pectin/chitosan/zinc oxide nanocomposite	Wastewater	Carbamazepine	68%	(Attallah et al. 2020)
Bacterial Cellulose	Wastewater	Microplastics	99%	(Faria et al. 2022)
Bacterial Cellulose	Bioremediation	Oil Spill Absorbents	-	(Fürtauer et al. 2021)

require regenerability and precise pollutant management (Rana et al. 2024, Ahmadi et al 2024).

Biopolymer Applications in Air Purification

Air pollution from particulate matter (PM), volatile organic compounds (VOCs), and toxic gases poses significant threats to human health and the environment. Biopolymer-based solutions have emerged for filtering airborne contaminants and catalyzing the degradation of pollutants (Gough et al. 2021, Ji et al. 2023). Table 5 lists various biopolymers and their environmental applications.

Electrospinning can produce chitosan nanofiber mats with high surface area and interconnected porous structures. These mats effectively capture delicate particulate matter (such as PM2.5 and PM10) and exhibit inherent antimicrobial properties, thereby improving indoor air quality. Functionalized cellulose membranes have been designed to enhance the removal of dust, allergens, and microbial contaminants. Their excellent mechanical and chemical stability makes them suitable for both indoor and industrial applications (Zhang et al. 2017, Lv et al. 2018, Borah et al. 2024).

Combining biopolymers with activated carbon yields composite filters that harness carbon's high adsorption capacity while retaining the biopolymer's biodegradability and processability. Such composites efficiently capture VOCs from indoor and industrial air environments (Akhtar et al. 2024). By immobilizing TiO_2 onto biopolymer supports (such as chitosan or cellulose), researchers have developed photocatalytic materials capable of degrading air pollutants such as NO_x and VOCs under light irradiation. This combination benefits from the biopolymer's adsorption properties and TiO_2's ability to generate reactive species that degrade contaminants (Balakrishnan et al. 2022, Wei et al. 2023). Biopolymers also serve as matrices for immobilizing enzymes that break down toxic pollutants. These bio-filters leverage microbial enzymatic activity to transform and remove contaminants from the air in an energy-efficient and eco-friendly manner (Abdelhamid et al. 2024).

Soil Remediation Using Biopolymers

Soil contamination from heavy metals, oil spills, pesticides, and industrial waste can reduce soil fertility and harm the environment. Biopolymers offer multiple approaches for remediating contaminated soils, including pollutant stabilization, nutrient delivery, and erosion control (Dhanapal et al. 2024). Chitosan forms complexes with heavy-metal ions through its amino and hydroxyl groups, reducing metal bioavailability in soil. This binding limits plant metal uptake and minimizes leaching into groundwater (Ahmad et al. 2017, Zheng et al. 2024).

Alginate hydrogels can encapsulate and immobilize heavy metals, reducing their mobility and bioavailability. These hydrogels help contain contaminants within the soil, thereby reducing the risk of environmental spread and plant uptake (Colin et al. 2024). Biopolymer matrices made from starch can be engineered to release nutrients gradually over time. This controlled-release mechanism minimizes nutrient runoff and soil depletion, supporting sustainable agricultural practices (Firmanda et al. 2024, Govil et al. 2024).

Coating seeds with chitosan has improved germination rates and enhanced plant resilience to environmental stresses. This treatment not only boosts early seedling growth but also protects against soil-borne pathogens (Samarah et al. 2020, Paravar et al. 2023). Hydrogels synthesized from xanthan gum and alginate enhance soil water retention and help prevent erosion. These materials support plant growth in arid environments and stabilize soils against wind and water erosion (Bajestani et al. 2025, Ali et al. 2024). Biodegradable mulch films derived from biopolymers are used in agriculture to reduce water evaporation, suppress weed growth, and maintain optimal soil temperatures. As they naturally degrade over time, they contribute to sustainable land reclamation practices (Menossi et al. 2021, Mansoor et al. 2022).

Biodegradation and Bioremediation Applications

Biopolymer-based carriers play a crucial role in supporting microbial-assisted degradation of pollutants, thereby enhancing overall bioremediation efficiency (Ayilara & Babalola 2023). Encapsulating bacteria within chitosan matrices creates a protective environment that enhances microbial survival and activity. In bioreactor applications, these encapsulated microbes degrade organic pollutants more efficiently due to sustained high-density microbial populations (Das et al. 2024).

Bioremediation beads composed of alginate or cellulose provide controlled release of biodegrading microbes into contaminated environments. These beads create a stable microenvironment that supports prolonged microbial activity, resulting in efficient pollutant degradation (Dzionek et al. 2016). Bacterial cellulose forms highly porous, lightweight sponges that absorb oil while allowing water to pass through. These properties make them practical for marine oil spill cleanup and reduce the environmental impact of oil contamination (ben Hammouda et al. 2021, Li et al. 2024). Chitosan-based materials have been developed into oil absorbents that are both biodegradable and efficient at selectively adsorbing oil from water. Their high adsorption capacity and ease of recovery provide a sustainable approach for oil spill containment and remediation in both marine and industrial settings (Mallik et al. 2022, Basem et al. 2024, Kaczorowska & Bożejewicz 2024).

FUTURE PERSPECTIVES AND CHALLENGES

Biopolymer-based environmental remediation strategies have demonstrated promising results, but challenges remain regarding scalability, cost, and long-term stability. Future research should focus on:

- Enhancing the mechanical strength and durability of biopolymer materials for large-scale remediation applications.
- Developing multifunctional biopolymer composites that integrate adsorption, catalysis, and biodegradation into a single system.
- Optimizing production processes to reduce costs and increase biopolymer availability for environmental applications.

CONCLUSIONS

Biopolymers have emerged as a compelling alternative to synthetic polymers, offering biodegradability, renewability, and functional versatility for environmental remediation. Their successful application in wastewater treatment, air purification, and soil restoration demonstrates their potential to mitigate pollutants ranging from heavy metals and dyes to microplastics. However, real-world implementation still faces significant hurdles, including biodegradation efficiency under mixed-contaminant conditions, high production and downstream processing costs, and limited mechanical robustness in large-scale deployments. To accelerate translation from the laboratory to the field, future research should prioritize improving the structural and chemical stability of biopolymer-based materials in complex, real-world environments while optimizing biosynthetic pathways to enhance yield, purity, and economic feasibility. Additionally, developing multifunctional composites capable of addressing multiple contaminants simultaneously is crucial. Scaling up cost-effective production methods using waste-derived substrates or engineered microbial systems and assessing environmental fate and lifecycle impacts under diverse remediation scenarios.

Equally important are policy and regulatory frameworks that can facilitate the shift toward biopolymer adoption. Incentives for biopolymer-based product development, stricter regulations on persistent plastics, and public procurement programs favoring biodegradable alternatives can significantly accelerate market uptake. Furthermore, standardizing testing protocols and safety assessments for environmental applications will be crucial for regulatory approval and public trust.

With continued interdisciplinary collaboration—spanning biotechnology, materials science, environmental engineering, and policy—biopolymers can play a transformative role in enabling a circular, sustainable bioeconomy.

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