Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 1, March 2026 issue

Type of the Paper (Review)

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

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Key Words	Biopolymers, Environmental remediation, Sustainable materials, Biodegradable adsorbents, Biodegradable polymers, Green technology, Biopolymer composites
DOI	https://doi.org/10.46488/NEPT.2026.v25i01.B4339 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Muthukumaran, P., Murugesan, K., Sureshbabu, P. and Jeyaseelan A., 2026. Biopolymers production strategies and its usage as clean material for environmental remediation. *Nature Environment and Pollution Technology*, 25(1), p. B4339. https://doi.org/10.46488/NEPT.2026.v25i01.B4339

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 caused by non-biodegradable synthetic polymers—derived primarily from fossil fuels—has emerged as a significant global concern due to their persistence, toxicity, and contribution to pollution in water, soil, and air. These synthetic materials not only deplete non-renewable resources but also generate long-lasting waste that poses threats to both ecosystems and human health (Kibria et al. 2023; Islam et al. 2024). In response to these challenges, biopolymers have garnered increasing attention as a sustainable alternative. Derived from renewable sources and often biodegradable, biopolymers offer promising advantages in terms of 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 in mitigating pollution and supporting 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 a highly biodegradable nature. Moreover, they can be biosynthesized from various biological resources. Biopolymers possess unique 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 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 repeating units. Fig. 1 illustrates various natural sources of biopolymers, along with examples.

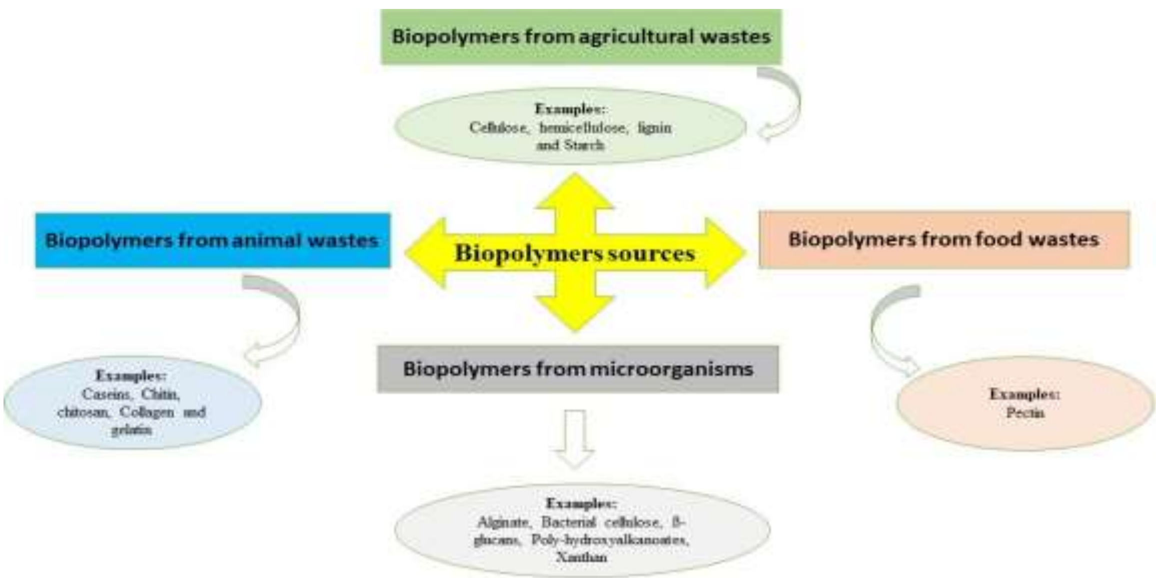

Fig 1. Biopolymers sources

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 literature and data, the method of biopolymer production encompasses biopolymers extracted from agricultural waste and animal origin, as well as similar biopolymers synthesized by classical chemical synthesis (e.g., polylactic acid, PLA). Additionally, polymers are produced from indigenous microorganisms 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).

2. 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 application (Das et al. 2024). Table 1 presents three significant types of biopolymers, along with their origins and 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

2.1 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 depends on non-renewable petrochemicals and generates long-lasting waste, biopolymers are often biodegradable, non-toxic, and derived from abundant natural resources. This shift aligns with the growing environmental regulations and increasing consumer demand for eco-friendly materials (Pinaeva and Noskov, 2024; Jha et al. 2024).

Among the most promising strategies in recent years is the cell factory approach, wherein microorganisms are genetically engineered to convert simple carbon sources—typically glucose, glycerol, or lignocellulosic hydrolysates—into high-value polymer precursors. Glucose, in particular, is favoured for its low cost, wide availability, and compatibility with many microbial systems. Using 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 and 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 for 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 compound, synthesized by Corynebacterium glutamicum and *E. coli* (Qian et al. 2009), serves as a monomer for nylon-4,6, a biodegradable polyamide. The 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 such as *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 through petrochemical synthesis, BDO is now biosynthesized by engineered microbes, such as E. coli and Clostridium species (Oliver et al.

2013; Kumar et al. 2020). BDO is a versatile precursor for biodegradable plastics, such as polybutylene succinate (PBS) and polybutylene terephthalate (PBT).

These advancements 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 for 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 their molecular weight, branching, crystallinity, and interaction 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 processes, high recovery and purification costs, limited tolerance of host organisms to toxic intermediates, and substrate competition within central metabolism all affect growth and productivity. To overcome these challenges, efforts are being 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 fulfils 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 and Gupta, 2024; Del Hierro et al. 2024).

2.2. 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 when using wild-type or unoptimized strains. Moreover, these processes typically require chemical catalysts and harsh solvents for polymer extraction and purification, resulting in increased environmental and economic burdens (Anderson et al. 2018; Kaur et al. 2024).

Currently, 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, posing 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 due to the accumulation of mixed metabolic byproducts (Sharma et al. 2024; Kaur et al. 2024).

One 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, curbing their potential applications. Synthetic biology addresses these challenges by enabling fine-tuned control over gene expression, modular pathway design, and the incorporation of non-natural monomers (Aravind et al. 2015; 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 utilized 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 the 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, such as 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 down the commercial deployment of such technologies. Despite these limitations, the integration of synthetic biology with computational modelling, machine learning, and high-throughput screening holds promise to accelerate the development of next-generation biopolymers. These polymers can be fully bio-based, biodegradable, and tailored for specific applications (Palladino et al. 2024).

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

3.1 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 and Noskov, 2024). Figure 2 illustrates various methods for preparing biopolymers. Table 2 Overview of the biopolymer synthesis pathway

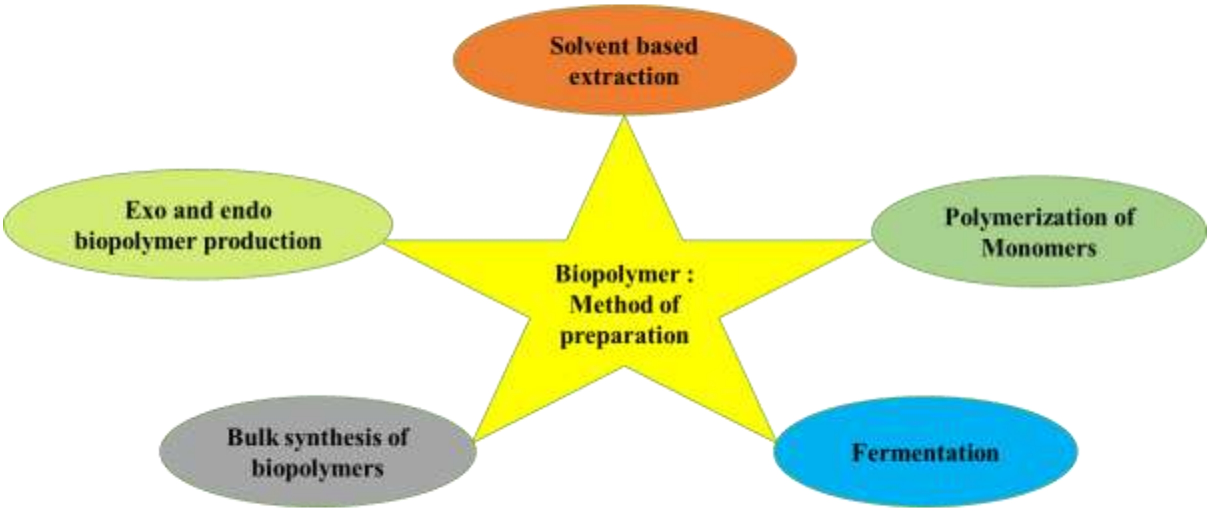

Fig. 2 Method of preparation of biopolymers

3.1.1 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.

3.1.2 Polymerization

The monomeric form of polymers is highly prepared for the synthesis of microstructure. 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 Overview of the biopolymer synthesis pathway

<table>
<tr><td rowspan="9">Direction of polymer synthesis</td><td>Glucose</td><td>Glucose</td><td>Glucose</td><td>Glucose</td></tr>
<tr><td>Glucose 6-phosphate</td><td>Glucose 6-phosphate</td><td>Acetyl coenzyme A</td><td>Glucose 6-phosphate</td></tr>
<tr><td>Glucose 1-phosphate</td><td>Glucose 1-phosphate</td><td>Oxaloacetate</td><td>Fructose 6-phosphate</td></tr>
<tr><td>Glucuronic acid - glucose</td><td>Glucuronic acid - glucose</td><td>Fructose 6-phosphate</td><td>Glucosamine 6-phosphate</td></tr>
<tr><td rowspan="5">Cellulose</td><td>N-acetylglucosamine 1-phosphate</td><td>Mannose 6-phosphate;</td><td>N-acetylglucosamine 6-phosphate</td></tr>
<tr><td>UDP-N-acetylglucosamine</td><td>Mannose 1-phosphate</td><td>N-acetylglucosamine 1-phosphate</td></tr>
<tr><td rowspan="3">Hyaluronan</td><td>GDP-mannose</td><td>UDP-N-acetylglucosamine</td></tr>
<tr><td>GDP-mannuronic acid</td><td>Chitin</td></tr>
<tr><td>Alginate</td><td>Chitosan</td></tr>
</table>

3.1.3 Solvent-based extraction.

In solvent-based extraction, the process is determined by mechanical operations, including sifting, filtration, and centrifugation of biomass for biopolymer extraction (Faidi et al. 2019). To improve efficacy, varying biopolymer solvents were extracted from pretreated biomass (Mahmood and Moniruzzaman, 2019). Similarly, to overcome the toxicity potential of solvents, 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).

3.1.4 Endo and exo biopolymer production.

Endo polymers, such as polyhydroxyoctanoate (PHO), possess unique characteristics and have low melting temperatures, allowing for the formation of lightweight composites (Van de Velde and Kiekens, 2002; Ujang et al. 2009). All these polymers are produced by eubacteria intracellularly. Similarly, *Ganoderma applanatum, Collybia confluens*, and *Pleurotus eryngii* were identified as potential sources of endopolymer. All these fungi can be cultivated using Mushroom Complete Medium (MCM) (Yang et al. 2007; Jeong et al. 2008; Moradali and 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 media 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).

3.1.5 Bulk synthesis

Biopolymers are extracted and synthesized from various sources, including microbes, plants, and natural renewable sources such as food and animal waste (Kaplan, 1998). The extraction method may differ from source to source. Generally, biopolymers are 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.* Various factors, including pH, substrate concentration, retention time, and substrate feeding rate, are necessary for the optimal production of biopolymers. Similarly, the genetic algorithm for fed-batch cultivation was studied using nutrient feeding rates and dilution rates to maximize PHB production (Khanna and Srivastava, 2005; Lai et al. 2013; Stanley et al. 2018).

4. PRODUCING BIO-BASED POLYMERS DIRECTLY VIA MICROORGANISMS

4.1 Alginate

Alginates are water-soluble, linear, anionic heteropolysaccharides. It is distributed in the cell wall of the algae family Phaeophyceae. Which include., *Laminaria hyperborean, Macrocystis pyrifera, Laminaria digitat,* and *Ascophyllum nodosum.* Besides algae, many bacterial species, such as Pseudomonas and Azotobacter, also produce alginate-like polymeric materials (Sabra and Deckwer, 2005; Abka-Khajouei et al. 2022).

4.2 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).

4.3 Xanthan

Xanthan is β-(1, 4)-linked heteropolymer with 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).

4.4 Gellan

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

4.5 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).

4.6 Polyhydroxyalkanoates (PHA)

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

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 and 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	(Kogan et al. 2007; Zakeri et al. 2017; Shikina et al. 2022)

			elements, and vitamins	
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)

4.7 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).

4.8 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).

5. PRODUCING BIO-BASED POLYMERS VIA ALGAE

Biopolymers are produced from algae in 3 ways: algal Fermentation, algal cell factories, and adding additives in 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.

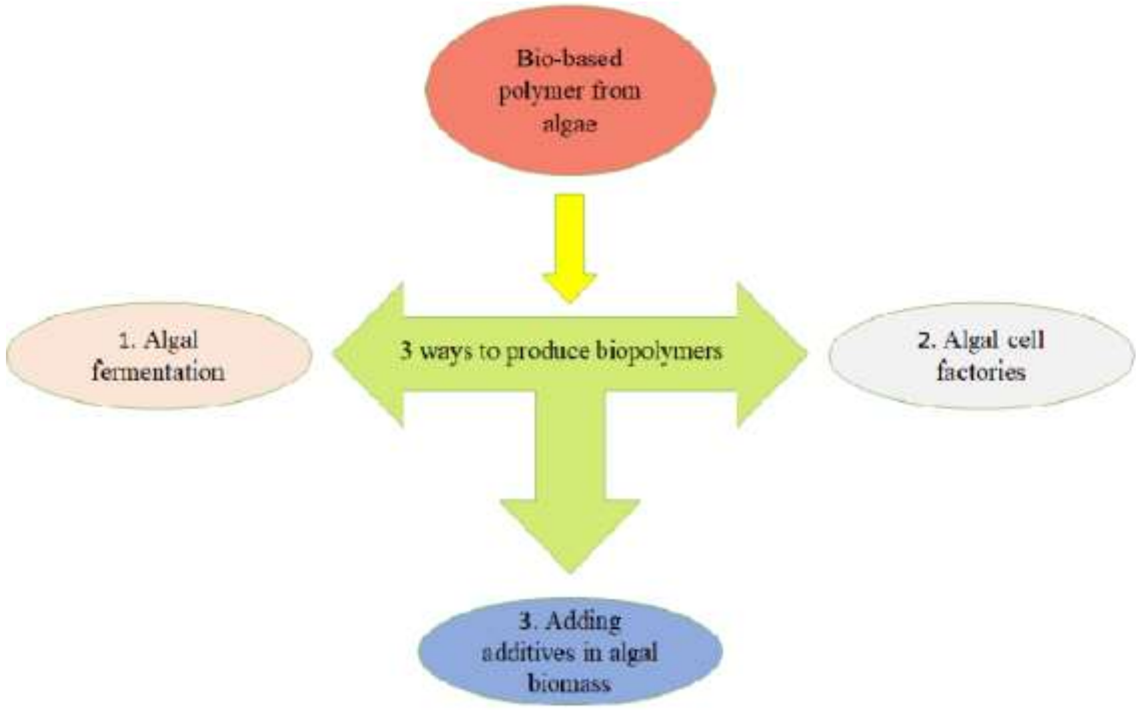

Fig. 3 Ways to produce bio-based polymers from algae

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 biocomposite (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% for κ-carrageenan was extracted from seaweed *Kappaphycus alvarezii* by using solvent 1-Butyl-3-methylimidazolium acetate by 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.

5.1 Comparative Insight on 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 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 and 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).

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*	
5	Alginate	*Sargassum muticum*	(Flórez-Fernández et al. 2019)
6	Fucoidan	*Nizamuddinia zanardinii*	(Alboofetileh et al., 2019)
7	Fucoidan	*Saccharica japonica*	(Saravana et al. 2018)
8	Carrageenan	*Mastocarpus stellatus*	(Ponthier et al. 2020)
9	κ-carrageenan	*Kappaphycus alvarezii*	(Gereniu et al. 2018)

6. ENVIRONMENTAL REMEDIATION APPLICATIONS OF BIOPOLYMERS:

The increasing environmental pollution resulting from industrialization, agricultural runoff, and urbanization has necessitated the search for sustainable remediation solutions. Conventional remediation strategies, such as the use of 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, such as chitosan, alginate, cellulose, starch, xanthan gum, and microbial exopolysaccharides, have significant potential in addressing water pollution, soil contamination, air purification, and hazardous waste management. These materials function through diverse mechanisms, including adsorption, filtration, chemical binding, encapsulation, and microbial-assisted degradation. The following sections provide an in-depth exploration of their applications in various environmental remediation domains (Kaur et al. 2024; Al-Hazmi et al. 2024).

6.1. Biopolymer-Based Materials for Wastewater Treatment

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

6.1.1 Adsorption of Heavy Metals and Toxic Ions

Heavy metals, such as 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 removing heavy metals (Verma et al. 2021).

Chitosan-Based Adsorbents: Chitosan, a deacetylated derivative of chitin, is widely studied due to 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 adsorption efficiency by increasing surface area and stability. Alginate-Based Adsorbents: Alginate, extracted from brown algae, contains carboxyl ($-COO^-$) groups, which 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, facilitating 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 are highly effective at binding heavy metals. Recent developments include the synthesis of Ca-alginate beads embedded with magnetic nanoparticles, which achieve high adsorption efficiency for Pb(II) ions while facilitating facile magnetic separation of the 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 reveal that adsorption processes on biopolymer-based materials follow 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 and Zare, 2024).

6.1.2 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 and 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 facilitating the degradation of 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 demonstrated to stimulate the production of reactive oxygen species (ROS), which expedite the degradation of complex organic dyes (Weon et al. 2023; Mendis et al. 2023).

Incorporating activated carbon into biopolymer matrices further improves the removal of dyes 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 achieve rapid adsorption of methylene blue, making them suitable for treating textile wastewater (Rehman et al. 2023; Kolya et al. 2023; Mittal et al. 2024).

6.1.3 Biopolymer-Based Membranes for Water Filtration

Biopolymer-based membranes and hydrogels have emerged as advanced solutions for water purification by combining sustainability with high filtration efficiency. Membranes fabricated from biopolymers, such as chitosan and cellulose acetate, exhibit high porosity, mechanical strength, and favourable surface charge properties. These features allow them to effectively remove 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 require regenerability and precise pollutant management (Rana et al. 2024; Ahmadi et al. 2024).

6.1.4 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 the filtration of airborne contaminants and the catalytic degradation of pollutants (Gough et al. 2021; Ji et al. 2023). Table 5 lists various biopolymers and their environmental applications.

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)

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, 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 can 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 like 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).

6.2 Soil Remediation Using Biopolymers

Soil contamination by heavy metals, oil spills, pesticides, and industrial waste can reduce soil fertility and harm the environment. Biopolymers provide 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 via its amino and hydroxyl groups, reducing metal bioavailability in the soil. This binding prevents 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 over time gradually. 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 offers protection 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).

6.3 Biodegradation and Bioremediation Applications

Biopolymer-based carriers play a crucial role in supporting microbial-assisted degradation of pollutants, thus enhancing overall bioremediation efficiency (Ayilara and Babalola, 2023). Encapsulating bacteria within chitosan matrices creates a protective environment that enhances microbial survival and activity. In bioreactor applications, these encapsulated microbes can more efficiently degrade organic pollutants 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 are excellent at absorbing 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 in 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 and Bożejewicz, 2024).

7. 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.

8. Conclusion

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 continues to face significant hurdles. These include biodegradation efficiency under mixed-contaminant conditions, high production and downstream processing costs, and limited mechanical robustness in large-scale deployments. To accelerate the translation from laboratory to 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 favouring 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.

Author Contributions: "Conceptualization J.A.; writing—original draft preparation, P.M.; writing—review and editing, J.A., P.M., M.K.., and P.S..; supervision, J.A.; project administration, J.A.; All authors have read and agreed to the published version of the manuscript." Authorship should be restricted to individuals who have made significant contributions to the research.

Funding: This review paper work received no external funding

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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