Kaur *et al.*
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REVIEW

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Biobased polymers of plant and microbial origin and their applications - a review

Rajwinder Kaur[1†], Loveena Pathak[1†] and Pratibha Vyas[1*]

Abstract

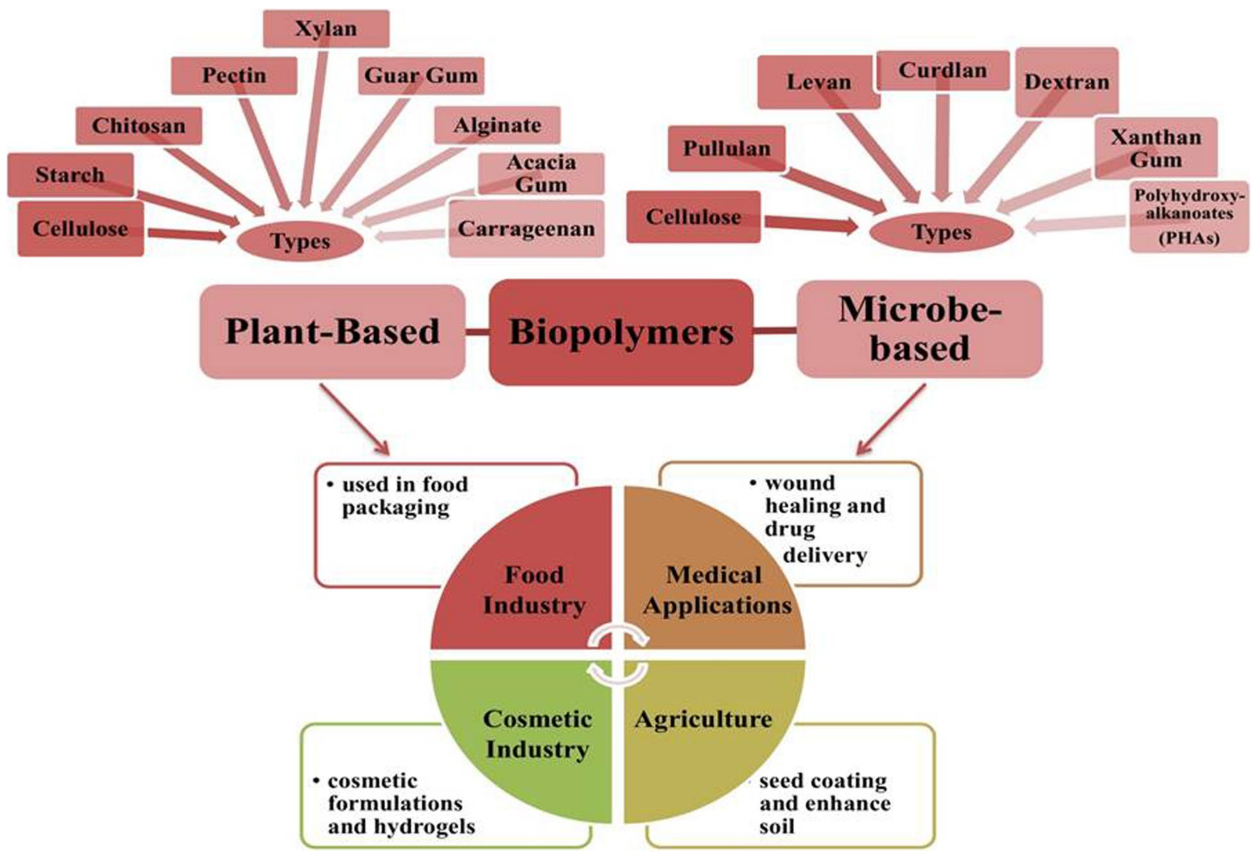
Synthetic polymers, which account for over 400 million tons of global production annually, are primarily composed of harmful chemicals that persist in the environment, leading to significant ecological and health issues. The global market for synthetic polymers is valued at approximately $31.46 billion in 2023, yet their environmental footprint is becoming increasingly untenable due to rising contamination levels and bioaccumulation. These synthetic polymers are recognized as major contributors to environmental degradation and pose severe risks to human health, with over 93% of Americans testing positive for plastic-related chemicals in their bodies. To mitigate these impacts, the industry is shifting towards biopolymers, which are projected to reach a market value of USD 38.5 billion by 2030, growing at a CAGR of 15.2%. Biopolymers derived from plants and microbes present a sustainable alternative due to their biodegradable and biocompatible nature. Plant-based biopolymers, such as those derived from agricultural residues, promote a zero-waste economy and have a lower environmental impact. Microbial production of biopolymers, using strains like *Agrobacterium*, *Erwinia*, *Bacillus* sp., *Pseudomonas* sp., and *Xanthomonas campestris*, is recognized for its efficiency and scalability. These biopolymers are increasingly used in high-priority markets, including the food industry, where they are valued for their safety and unique properties, and the medical and pharmaceutical sectors, where they serve as biocompatible materials for drug delivery and tissue engineering. The present review mainly focuses on the various plants- and microbes-based biopolymers and their applications in different industries.

Keywords Synthetic polymers, Biopolymers, Biodegradation, Microbial polymers, Sustainable alternatives

†Rajwinder Kaur and Loveena Pathak contributed equally to this work.

*Correspondence:
Pratibha Vyas
vyasp2000@pau.edu
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

The inception of synthetic polymers dates back to 1869 when John Wesley Hyatt developed the first synthetic polymer as a replacement for ivory. Leo Baekeland then introduced Bakelite in 1907, marking the emergence of the first fully synthetic plastic devoid of naturally occurring molecules. The expansion of the plastic industry gained momentum during World War II, leading to the widespread adoption of synthetic polymers in various applications. Today, synthetic polymers are integral to modern life, found in countless products and industries [41]. The global synthetic polymers market reflects this continued growth and importance, with an estimated value of USD 24.97 billion in 2024, expected to rise to USD 35.61 billion by 2031. This growth is driven by a compound annual growth rate (CAGR) of 5.2% from 2024 to 2031 (source: coherentmarketinsights). However, the widespread use of synthetic polymers is not without significant ecological and health concerns. Despite their ubiquity, only about 9% of all plastics produced have been recycled [49]. Projections indicate that by 2050, around 12,000 million metric tons of plastic waste could accumulate in landfills or the environment. Microplastics, which are now found in the air, water, soil, food, and even human blood, present alarming health risks. A recent study revealed the presence of microplastics in the blood of 17 out of 22 healthy individuals, highlighting the pervasive nature of this contamination [58, 59]. Additionally, many synthetic polymers contain harmful additives such as phthalates and bisphenols, which can leach into the environment and cause endocrine disruption [88]. These chemicals are associated with severe health issues, including infertility, obesity, diabetes, and cancer [25]. If current trends continue, plastic production and disposal could account for 13% of the global carbon budget by 2050, underscoring the urgent need to address these environmental and health impacts [113].

To combat these challenges, advances in both mechanical and chemical recycling are essential for improving polymer waste management. Mechanical recycling processes are being refined to handle a broader variety of plastics [128], while chemical recycling technologies are being developed to convert mixed plastic waste into valuable raw materials, reducing reliance on new resources and enhancing recycling rates [46]. Innovative technologies such as advanced sorting systems and chemical depolymerization methods are also emerging, enabling the breakdown of plastics into their constituent monomers for reuse [21].

The pursuit of alternatives to synthetic polymers is equally vital, with biopolymers offering a promising path forward. Biobased polymers, derived from plant and microbial sources, represent a sustainable solution with diverse applications across industries. Biopolymers are non-hazardous and biocompatible, sourced from living organisms like plants, animals, and microorganisms. They can be directly synthesized within living cells or chemically synthesized using materials from living cells. Due to their non-toxic, biodegradable nature, biopolymers serve as excellent alternatives to synthetic polymers in mitigating environmental concerns [55].

The global market for bioplastics and biopolymers was valued at approximately USD 14.3 billion in 2023 and is anticipated to grow to USD 38.5 billion by 2030, reflecting a compound annual growth rate (CAGR) of 15.2% from 2023 to 2030. This significant growth is driven by advancements in biotechnology, increasing consumer awareness of environmental sustainability, and the expanding use of biopolymers across various sectors (Source: globenewswire). Biopolymers are available in various forms, including polypeptides, polysaccharides, and polynucleotides [19].

They can be broadly classified into two categories based on their origin. Plant-derived biopolymers, such as cellulose, starch, and hemicellulose, have long been valued for their abundance and versatility [42]. Meanwhile, microbial biopolymers, including polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), polylactic acid (PLA) and bacterial cellulose, are gaining attention for their biodegradability and customizable properties. The development and adoption of biopolymers offer a promising avenue toward addressing the environmental challenges posed by synthetic polymers [39].

The widespread adoption of biopolymers across industries marks a pivotal moment in the quest for sustainable solutions to contemporary challenges. Derived from natural sources such as plants and microorganisms, biopolymers have emerged as versatile materials with a myriad of applications. They are increasingly employed in fields including food packaging, medical uses, cosmetics, agriculture, wastewater treatment, and industrial processes. For instance, polylactic acid is widely used in the automotive sector due to its mechanical strength. Notably, Toyota first employed this polymer to make a wheel cover for the Toyota Raum [104]. In the textile industry, biopolymers such as chitosan, cellulose ethers, and alginate serve various purposes, including acting as binding agents, leveling agents, and viscosity modifiers, respectively [48]. These biodegradable and renewable materials play a crucial role in advancing sustainability, reducing ecological footprints, and decreasing reliance on fossil fuels.

These biodegradable and renewable materials play a crucial role in advancing sustainability efforts, reducing ecological footprints, and diminishing reliance on fossil fuels [83]. With their distinctive properties and compositions, biopolymers serve various purposes in biomedical engineering, tissue engineering, drug delivery systems, packaging, construction, electronics, and beyond. Additionally, the performance of biobased polymers can be enhanced through various modifications, expanding their range of applications. Techniques such as esterification and etherification, the incorporation of nanoparticles to improve thermal stability, and copolymerization by blending with other polymers to create biopolymers with tailored properties, all contribute to making biopolymers ideal alternatives to conventional polymers. Their versatility and environmentally friendly characteristics position them as promising solutions for fostering a greener and more sustainable future across diverse sectors [27]. This review provides an in-depth exploration of the diverse realm of biopolymers, shedding light on their wide-ranging applications and offering a comprehensive understanding of these sustainable materials. By exploring the various industries that benefit from biopolymers, it uncovers their multifaceted roles and the potential they hold in advancing sustainability across different sectors.

Plant based biopolymers

Plant-derived biopolymers represent a sustainable and environmentally-friendly class of materials sourced from renewable plant origins. They present a biodegradable substitute for conventional petroleum-based and synthetically derived polymers, contributing to a reduced reliance on chemicals and finite fossil fuel resources. Frequently encountered instances of plant-derived biopolymers encompass cellulose, chitosan, and starch, which are obtained from a diverse range of plants such as wheat, rice, potatoes etc. (Fig. 1; Table 1). With properties such as biodegradability, biocompatibility, and the potential for tailored functionalities, plant-based biopolymers are increasingly being adopted across industries like packaging, agriculture, personal care, and biomedical applications [16, 115]. The following are among the most prevalent plant-derived biopolymers:

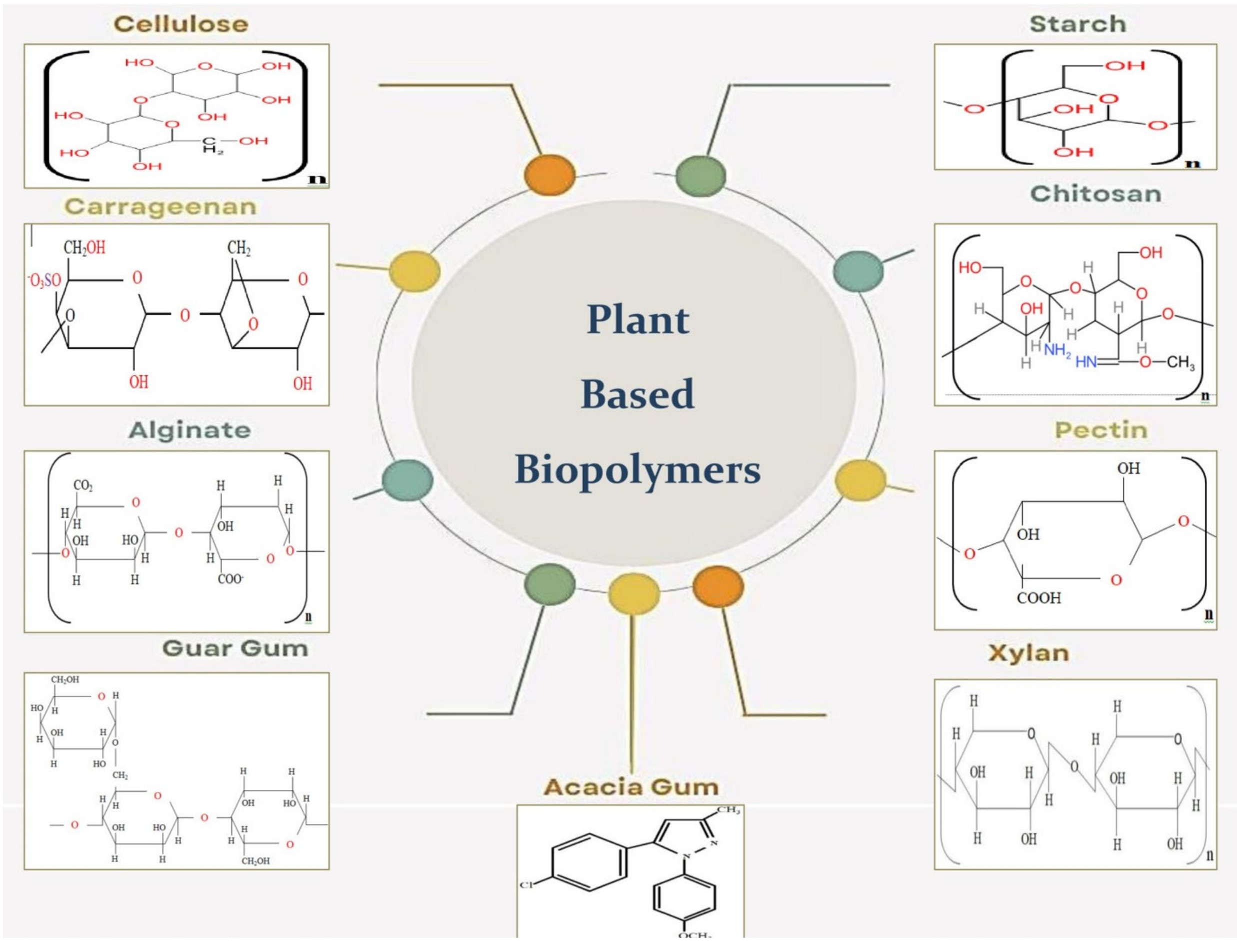


Fig. 1 Plant based biopolymers

Cellulose

Cellulose, the most abundantly present carbohydrate, is a naturally stable nontoxic biodegradable polymer primarily present in nature within microfibrils found in the cell walls of various types of wood (like softwood, spruce, cedar and hardwood) and plants (like flax, hemp, cotton, and ramie). The monomer unit in cellulose is glucose, attached by β(1→4) glycosidic linkages. Cellulose possesses a complex hierarchical structure, comprising aggregates of extremely fine fibrils containing multiple cellulose chains, which are then arranged to form cellulose fibers. These fibers are further organized into filamentous structures through wet extrusion. Additionally, cellulose microfibrils can also aggregate to form either microcrystalline cellulose or cellulose nanocrystals. Although wood cellulose is the most common source for pharmaceutical-grade microcrystalline cellulose, cellulose nanocrystals can be derived from various sources, including wood cellulose and plant cellulose [109]. Plant cellulose can be chemically modified to form derivatives like hydroxypropyl methylcellulose, sodium carboxymethyl cellulose, hydroxyethyl cellulose [84] carboxymethyl cellulose, cellulose xanthate, cellulose nitrate [102], cellulose ether, cellulose ester, cellulose acetate and cellulose sulfate [109], expanding its applications in the pharmaceutical and biomedical fields. Cellulose is also widely used in beauty products, agricultural chemicals and for the formation of cellophane films.

Starch

Starch, ranking as the second most prevalent polymer in nature following cellulose, has been extensively researched for various sustainable industrial applications. This polysaccharide consists of two glucan polymers, namely amylose and amylopectin, connected via α-1,4- and α-1,6-glycosidic bonds [10]. The different proportions of these components in various starch sources like corn, potato, rice, wheat, maize, barley and cassava facilitate the utilization of unconventional starch sources in the production of edible films. Starch, whether in its original state or after modification, is frequently employed as a film-forming substance to

Table 1 Plant-based biopolymers and their applications

Biopolymer	Sources	Polymer Composition	Polymer Properties	Applications	Reference
Cellulose	Plant cell wall	Linear polymer of β-1,4-linked D-glucose units	Renewable, biodegradable, biocompatible, good physical and biological characteristics, enhances mechanical strength and stiffness of composites	Tissue engineering scaffolds, wound and burn dressings, medical implants, drug delivery systems, packaging materials	Das et al. 2023 [26]
Starch	Plant seeds (e.g.,corn and wheat) and tubers (e.g., potatoesand cassava)	Composed of amylose and amylopectin polysachharides	Biodegradable, thermoplastic, exhibits good film-forming properties	Drug delivery application and in paper and cardboard manufacturing	Watcharakitti et al. 2022 [129]
Xylan	Cell wall of wood and annual plants	Composed of 1,4-β-D-xylopyranose units with branched carbohydrate chains	Biodegradable, film-forming ability, variable mechanical strength depending on composition and processing conditions	In paper industry, textile printing and as sweetener and preservative in various food products	Nechita et al. 2021 [85]
Chitosan	Mushrooms	Polysaccharide composed of β-(1–4)-linked D-glucosamine units with varying degrees of N-acetylation	Biodegradable, biocompatible, non-toxic, exhibits antimicrobial, and bacteriostatic properties, good film-forming ability	Food packaging material, pharmaceutical applications, waste product valorization	Alimi et al. 2023 [8]
Pectin	Primary cell wall of terrestrial plants	Heteropolysaccharide composed of α-1,4-linked D-galacturonic acid residues with varying degrees of methyl esterification and O-acetylation	Biodegradable, biocompatible, exhibits pH-dependent solubility, forms gels in the presence of calcium ions or at low pH	Wound dressings, tissue engineering scaffolds, and drug delivery systems due to their mucoadhesive properties and injectable hydrogels, antibacterial and anticancer activities	Sultana 2023 [120]
Guar Gum	Guar Seed	Composed mainly of galactomannan, consisting of a backbone of β-D-1,4-linked mannose residues with side chains of α-D-galactose residues	exhibits pseudoplastic (shear-thinning) behaviour, biodegradable	Application is food emulsion, dietary supplement in broiler diets and supplementing it with β-mannanase to which restores the microbiota composition	Saha et al. 2017 [106], Tahmouzi et al. 2023 [123]
Alginate	Extracted from the cell walls of red seaweeds (Rhodophyta)	Linear copolymer composed of alternating blocks of α-(1 ⟶ 4)-linked L-guluronic acid and β-(1 ⟶ 4)-linked D-mannuronic acid residues	Biodegradable, biocompatible, forms gels in the presence of divalent cations	Used in drug delivery systems, food thickening agents, stabilizer in emulsions, tissue engineering and as a component in biodegradable packaging materials	Szabó et al. 2020 [122]
Carrageenan	Extracted from the cell walls of red seaweeds (Rhodophyta)	Composed of linear polysaccharides, primarily consisting of alternating units of D-galactose and 3,6-anhydrogalactose	Biodegradable, biocompatible, forms gels in the presence of potassium or calcium ions, exhibits excellent thickening and stabilizing properties	Used in food products as a thickening agent, for drug delivery systems, potential in developing hydrogels and composite materials	Pacheco-Quito et al. 2020 [89]
Acacia Gum	Bark of Acacia tree	A complex mixture of polysaccharides (primarily arabinogalactan) and glycoproteins	non-toxic, biodegradable, excellent emulsifying and stabilizing properties	Used as a thickener, stabilizer, tissue engineering, used in enhanced oil recovery	Koyyada and Orsu 2021 [54], Adewunmi et al. 2022 [4], Abou-alfitooh et al. 2024 [2]

produce biodegradable and ingestible films and coatings. The elevated amylose content inherent in starch is particularly desired as it contributes to the production of films with favorable technological characteristics [87]. Starch-based biopolymers are a natural, bio-based alternate to conventional petroleum-derived plastics such as polystyrene, which are lightweight and often employed in packaging applications [37]. Additionally, starch has a high demand in paper, textile, adhesive and cardboard industries [129].

Chitosan

Plant-based chitosan stands out as a significant biopolymer with diverse applications spanning agriculture, healthcare, and various industries. Chemically known as poly (1,4-β-D-glucopyranosamine), chitosan represents a de-acetylated form of chitin, a substance present in the exoskeletons of arthropods like lobsters, shrimps, and crabs, as well as in the cell walls of fungi. Plant-derived chitosan, sourced from mushrooms or *Aspergillus niger*, offers a sustainable, animal-free alternative. Recognized for its biodegradability, environmental friendliness, and compatibility with living organisms, this biopolymer finds suitability in sustainable agriculture, food production, and cosmetics. Plant-derived chitosan has been observed to stimulate plant growth by modulating various physiological processes, thereby enhancing crop yield, quality, and natural defense mechanisms. Moreover, chitosan exhibits a broad spectrum of properties including antifungal, antibacterial, antiviral, and bio-nematicidal effects, making it invaluable across various applications. Its versatility extends to the pharmaceutical industry, aiding in drug delivery, as well as biomedical fields like bone and tissue regeneration, and cosmeceuticals [28].

Pectin

Pectin, a complex heteropolysaccharide, serves as a significant multifunctional constituent of the cell wall in numerous terrestrial plants. Primarily composed of subdomains known as xylogalacturonan, rhamnogalacturonan I, rhamnogalacturonan II, which are linked to the homogalacturonan skeleton, pectin consists of approximately 70% galacturonic acid. Citrus fruit peels are widely recognized as the primary source for industrial-scale pectin extraction due to their favorable properties and high yield. Various methods, including hydrothermal-assisted extraction, ultrasound-assisted extraction, hydrodynamic cavitation, microwave-assisted extraction, subcritical water extraction, and enzyme-assisted extraction, have been utilized to extract anionic biopolymer pectin from organic peel waste [68]. It finds extensive use in the food production sector for its functions such as a thickening, emulsifying, gelling, stabilizing and coating. In the biomedical field, it is utilized in gene and drug delivery, cholesterol reduction, wound healing, and as a micro- and nano-encapsulating agent for controlling the release of active ingredients with various functionalities [36].

Xylan

Hemicelluloses are composed of β-D-pyranol residues linked in a 1, 4 configuration,and are categorized into three main sub-groups: xylans, mannans, and xyloglucans. Xylan, the most abundant type, is composed of β-D-xylopyranosyl (xylose) units connected via β-1–4 glycosidiclinkages [118]. The forms of branching originating from the β-D-xylopyranosyl backbone are dictated by the source of xylan, leading to subcategories of xylan, such as arabinoxylan (found in cereal grains), homoxylan (found in seaweed and in algae), arabinoglucuronoxylans (found in grass) and glucuronoxylan (predominant hemicellulose component of hardwood). Non-toxic and biocompatible characteristics of xylan make it suitable for various biocomposite applications. Through various chemical methods, it can be transformed into bioplastics for packaging, xylan-based hydrogels for water remediation, and can also be transformed into chemicals like lactic acid, xylitol, furfural and ethanol [82]. Most major sources of xylan are *Pinus pinaster* wood and *Eucalyptus globulus* wood. Other common sources include almond shell, corn cobs and rice husk [103].

Guar gum

It is extracted from seeds of the plant *Cyamopsis tetragonolobus*, predominantly cultivated in India and Pakistan. It constitutes a galactomannan polysaccharide comprising a linear arrangement of (1→4)-linked β-D-mannopyranosyl units, with (1→6)-linked α-D-galactopyranosyl residues serving as side chains, essentially featuring a mannose backbone with galactose side chains [77]. Guar gum is esteemed as a valuable biopolymer for its distinctive attributes, notably its capacity to establish hydrogen bonds with water molecules, resulting in thickening and stabilizing capabilities. Consequently, it finds extensive application across various sectors including food, pharmaceuticals, textiles, and oil. Within the food industry, guar gum acts as a thickener, stabilizer, and emulsifier in a wide array of products such as ice cream, sauces, beverages, baked goods, meat items and it also serves as a dietary fiber supplement. Furthermore, it is broadly used in cosmetic industry in manufacturing of shaving creams, toothpastes, shampoo, mists, hair dyes and dry face masks etc. [121].

Alginate

Different sources of alginate include *Sargassum*, *Laminaria*, *Nacrocystis*, *Marcocystsporifera*, *Ascophyllum*, *Alario* and *Eisenia* [5]. Alginate is a naturally occurring, linear, and anionic polysaccharide abundant in nature, which is primarily sourced from the cell walls of brown seaweeds of the Phaeophyceae class. Its composition consists of 1,4-α-L-guluronic acid residues and 1,4-linked-β-D-mannuronic acid in its structure. Alginate possesses numerous advantageous qualities that render it a valuable plant-derived biopolymer. These include its ability to form hydrogels as well as its biodegradability, biocompatibility, biodegradability and non-toxic nature. These attributes have contributed to its widespread adoption across diverse industries, encompassing pharmaceuticals, biomedicine, and agriculture [3]. In the agricultural industry, alginate is used as a superabsorbent polymer, a coating for seeds, fruits, and vegetables, and as a carrier for plant-growth-promoting microorganisms and biocontrol agents [66].

Acacia gum

Acacia gum, commonly referred to as gum arabic, is a naturally sourced biopolymer derived from plants, specifically extracted from the sap of different Acacia tree varieties, particularly *Acacia seyal* and *Acacia senegal*. This intricate polysaccharide is characterized by its branching structure and comprises galactose and arabinose residues [7]. Mukherjee and Mullick [78] conducted a study investigating the optical properties of acacia gum modified with black grape and eggplant chromophores, comparing them to the unmodified form. The research concluded that the chromophore-modified Gum Acacia meets the necessary criteria, rendering them as promising materials for applications in DSSCs. Acacia gum has also been researched for its potential as a prebiotic by Rawi et al. [99], as it possesses the capacity to specifically enhance the proliferation of advantageous gut bacteria. This discovery has resulted in its application as a dietary fiber supplement and in the creation of functional food products. Furthermore, it has a wide-ranging application in the pharmaceutical, cosmetic, food and other industries as a thickening agent, emulsifier and stabilizer.

Carrageenan

Carrageenan is a sulphated polysaccharide composed of α-1,3 and β-1,4 glycosidic linkages connecting D-galactose units and 3,6-anhydro-galactose units. It is mainly obtained from marine plants belonging to family Rhodophyceae commonly called Red algae [92]. It serves as an anti-inflammatory substance and finds application as a thickener, binder, stabilizer, gelling and wetting agent across various industries, both food and non-food. Its utilization extends notably within dairy farm products [7]. Fatehi et al. [34] explored carrageenan's potential for soil treatment, discovering its promising qualities such as shear-thinning behavior, soil stabilization abilities, resistance to degradation, and versatility. These findings suggest carrageenan could be a valuable solution for improving soil mechanics and tackling geotechnical issues.

Microbial-based biopolymers

Apart from plants, microorganisms also serve as a good candidate for obtaining different types of biopolymers. Some important biopolymers of microbial origin include pullulan, levan, curdlan, cellulose, xanthan gum, polyhydroxyalkanoate, polyhydroxybutyrate etc. with wide applications (Table 2; Fig. 2).

Pullulan

It is an exopolysaccharide, consisting of maltotriose units with α-1,6glycosidic bonding. It is mainly obtained as a water-soluble polysaccharide from a polymorphic fungus *Aureobasidium pullulans* [43]. R. Bauer made the discovery of microbial pullulan production by *Pullularia pullulans* in 1938.In comparison to traditional polymers, pullulan has been reported to enhance the tensile strength by 6–37 times and prolongs bio-adhesion time by 72–120 times [80]. Pullulan has a unique characteristic that is it impermeable to oxygen so it can be used as blood plasma substitute. *Tremella mesenterica*, *Cryphonectria parasitica*, *Teloschistes flavicans*, *Rhodotorula bacarum*, *Cytaria harioti* and *C. darwinii* are other reported microorganisms for pullulan production [111, 117]. The biosynthesis of pullulan involves several key genes that encode enzymes responsible for its production. For instance, Pullulan Synthase (AGSII) enzyme is critical for the polymerization of glucose units into pullulan. Studies have identified the AGSII gene in *A. pullulans*, which is responsible for catalyzing the transfer of glucose from uridinediphosphoglucose (UDPG) to the growing polysaccharide chain. Additionally, transformation systems, such as plasmid vectors, have facilitated the introduction of specific genes into *A. pullulans* to create overproducing strains [22]. Modified pullulan finds extensive applications across the food, pharmaceutical, cosmetics, and biomedical industries. It has high demand in paper industry because of its good glue capacity.

Table 2 Microbial biopolymers and their applications

Biopolymers	Microorganisms	Polymer Composition	Polymer Properties	Applications	Reference
Pullulan	*Aureobasidium pullulans*; *Tremella mesenterica*, *Cryphonectria parasitica*, *Teloschistes flavicans*, *Rhodototula bacarum*, *Cytaria harioti*, *C. darwinii*	Maltotriose repeating units with α-(1 → 4) and α-(1 → 6) glycosidic bonds	Water-soluble, non-toxic, non-mutagenic, excellent film-forming and adhesive properties, biodegradable	**Food industry**: Preservative; prebiotic for bifidobacteria; low viscosity filler in sauces and beverages; stabilizer and binder in food pastes; films for packaging dry fruits; edible film in mouth fresheners and oral hygiene products **Cosmetics**: Additive and thickener; **Pharmaceuticals**: adhesive; coating; films in oral care products; blood plasma expander	Singh et al. 2008 [117]; Singh et al. 2017 [116]
Levan	*Bacillus subtilis*, *B. amyloliquefaciens*, *Corynebacterium*, *Erwiniaherbicola*, *Mycobacterium*, *Paenibacillus*, *Streptococcus*, *Acetobacter*, *Zymomonasmobilis*, *Pseudomonas* and *Aerobacter*	A homopolymer composed primarily of β-(2,6)-linked fructose units, with a glucose residue at the end	Water-soluble, biodegradable, non-toxic, exhibits excellent emulsifying and thickening properties	**Food industry**: Emulsifier; stabilizer; thickener; sweetener; source of fructooligosaccharides; prebiotic for *Megasphaera* and *Megamonas*; component of edible films; increases short-chain fatty acid levels with biocontrol properties **Cosmetics**: Cosmeceutical and skin-regenerating preparations; inhibits tyrosinase leading to decreased melanin production **Pharmaceuticals**: carrier; stabilizer; healing of burns; local skin antifungal therapy with amphotericin B; preparation of hydrogels for wound healing	Srikanth et al. 2015 [119]; Zhang et al. 2019 [132]; Cheng et al. 2021 [23]; Domżał-Kędzia et al. 2023 [31]
Bacterial cellulose	*Agrobacterium*, *Aerobacter*, *Achromobacter*, *Alcaligenes*, *Azotobacter*, *Cluconacetobacter*, *Komagataeibacter*, *Pseudomonas*, *Dickeya*, *Rhizobium*, *Rhodobacter* and *Sarcina*	Composed of β-1,4-linked glucose units, similar to plant cellulose but with higher purity and crystallinity	Biodegradable, biocompatible, high tensile strength, water-holding capacity, and porosity	**Food industry**: thickener; suspension agent; used in traditional dessert, vegetarian meat, low cholesterol diet, food/beverage additives, and food packaging **Personal Care products:** face masks **Biomedical Area:** wound dressing in treating various ulcers, abrasions, burns, skin grafts, post-operative surgical wounds, and lacerations; dental implant; artificial skin, drug delivery, vascular grafts; biosensor	Senni et al. 2011 [112]; Portela et al. 2019 [94]; Zhong 2020 [134]

Table 2 (continued)

Biopolymers	Microorganisms	Polymer Composition	Polymer Properties	Applications	Reference
Curdlan	*Bacillus*, *Rhizobium*, *Agrobacterium*, *Alcaligenes*, *Cellulomonas*	Composed of a homopolymer of D-glucose linked with β-(1,3)-glucan	Water-insoluble, thermally stable, forms elastic gels upon heating in aqueous suspension	**Food Industry**: Stabilizer, gelling, thickener and texture modifier in noodles, patties, sausages, gravies etc.; food packaging; antioxidant; used in low caloric food due to no caloric value **Pharmaceutical and biomedical industry:** antitumor and antimicrobial; triggers phagocytosis; encapsulation of drugs; drug delivery system	Lee et al. 1999 [56]; Mohsin et al. 2020 [73]; Aquinas et al. 2022 [11]
Xanthan Gum	*Xanthomonas campestris*	Composed of β-1,4-linked glucose units, similar to plant cellulose but with higher purity and crystallinity	Biodegradable, biocompatible, high tensile strength, water-holding capacity, and porosity	**Food Industry**: used in puddings, yoghurts and jellies due to its gelling property **Pharmaceutical Industry**: used in toothpastes, ointments and as auxiliary substance in tablets **Soil Properties:** reduces permeability, increase density and enhances mechanical properties of soil	Prakash et al. 2013 [95]; Ayeldeen et al. 2016 [13]; Lee et al. 2017 [57]
Polyhydroxyalkanoates (PHAs)	*Ralstonia eutropha*, *Bacillus megaterium*, *Pseudomonas putida*, *Halomonas alkaliantarctica*	Composed of hydroxyalkanoic acid monomers linked by ester bonds	Biodegradable, biocompatible, thermoplastic, piezoelectric, pyroelectric, and ferroelectric properties	**Biomedical Industry**: preparation of biodegradable films and containers, post-operative adhesions and as sutures **Agriculture**: encapsulations of biofertilizers **Biomedical Industry**: used in biodegradable products	Aggarwal et al. 2020 [7]; Sikkema et al. 2023 [114]; Mozejko-Ciesielska et al. 2023 [76]

Levan

It is starch-based biopolymer with fructose units joined together in the main chain by β-2,6-glycosidic bonds and β-2,1 in branching structure. The synthesis of levan includes the breakdown of sucrose into fructose as well as glucose by levansucrase enzyme produced by microorganisms, whereby the fructose units are transferred from sucrose by the enzyme to form β-2,6-glycosidic bonds and levan formation. Thelevanase enzyme, breaking down the β-2,6-glycosidic bonds, is responsible for digestion of levan resulting in the release of the fructose as the main metabolite. Species of *Corynebacterium*, *Mycobacterium, Bacillus*, *Streptococcus*, *Acetobacter*, *Zymomonas*, *Erwinia*, *Pseudomonas* and *Aerobacter*are various levan producing bacterial species [7]. The levan produced by bacteria have the molecular weight around 500,000 daltons with broad-spectrum activities and applications [24, 30]. It demonstrates varied viscosity, solubility and stability, which are contingent upon its origin and the conditions of production. It is a strong antioxidant, therefore, has hyperglycemic inhibiting, anticancer and anti-HIV properties [62]. It is thermostable with liquefying point temperature near 225˚C and shows resistance against invertase and amylase. Because of its colloidal nature, it is used as food thickener and in cosmetic industries.

Bacterial cellulose

It is an exopolysaccharide with fibers ranging between 20–100 nm diameter, produced by numerous bacterial species such as *Agrobacterium*, *Aerobacter*, *Achromobacter*, *Alcaligenes*, *Azotobacter*, *Gluconacetobacter*, *Komagataeibacter*, *Pseudomonas*, *Dickeya*, *Rhizobium*, *Rhodobacter* and *Sarcina* etc. Among these, *Gluconacetobacter xylinus* earlier known as *Acetobacter xylinus* stands as the earliest identified and extensively researched microorganism for bacterial cellulose production [133]. The bacterium *Komagataeibacter* is a model organism for microbial cellulose production and research purposes [7]. The key genes involved in bacterial cellulose biosynthesis are bcsA, bcsB, and bcsC. These genes produce proteins that constitute the cellulose synthase complex, essential for the polymerization of glucose into cellulose chains [32, 63]. Bacterial cellulose has exceptional water retention owing to its high hydrophilicity and extensive surface area-to-mass ratio [134]. Moreover, it showcases impressive mechanical strength, high crystallinity, and cost-effective production. It is more accepted than plant cellulose because it is free from pectin, hemicelluloses and lignin and its purification and cleaning is much easier than plant cellulose. Microbial cellulose is a good alternative of xanthan gum for thickener in biomedical applications [7].

Curdlan

Curdlan is a bacterial exopolysaccharide with β-(1,3)-glycosidic bonding, obtained from bacteria including species of *Rhizobium, Agrobacterium, Alcaligenes, Cellulomonas,* and *Bacillus* etc. mainly by the submerged fermentation [65]. Curdlan synthesis was initially noted in *Alcaligenes faecalis* var. *myxogenes* 10C3 in 1962 by Harada and his team [44]. The main genes involved in curdlan biosynthesis are crdA, crdB, and crdC. These genes produce proteins that are vital for the polymerization of glucose units into curdlan. Specifically, crdA plays a key role in synthesizing the polysaccharide backbone, while crdB and crdC contribute to the regulation of curdlan production [52]. Curdlan has glucose subunits that repeat, linked by a β bond between the first and third carbons of the glucose ring. It is known to produce gels with colorless, tasteless and odorless properties. It has gelling property that makes it useful in food and biomedical industry [56]. Curdlan received approval from the U.S. Food and Drug Administration (FDA) for use in the food industry in 1996 and later approved in Korea, Taiwan and Japan in 1989.

Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates (PHAs), the sole polymer boasting over 150 variations, represent a biodegradable plastic initially uncovered by Lemoigne in 1925, synthesized within microorganisms. Their diversity stems from the varying carbon atom count within their monomers, yielding a spectrum of types and structures [110]. Among prokaryotes, poly-3-hydroxybutyrate stands as the major prevalent PHA comprised of repeating units of (R)-3HB monomers that polymerize into a chain. PHAs are broadly categorized into short chain length (scl-PHAs) such as poly(3-hydroxybutyrate); medium chain length (mcl-PHAs) such as poly(3-hydoxyhexanoate), and long chain length (lcl-PHAs) such as Poly(3-hydroxypentadecanoate) with 3–5, 6–14 and greater than 14 carbon atoms respectively [79]. The primary genes involved in PHA synthesis are the phaC genes, which encode PHA synthase enzymes. These enzymes catalyze the polymerization of hydroxyalkanoate monomers into PHA polymers. Recent research has identified various classes of PHA synthases, such as Class I and Class II, which differ in substrate specificity and polymerization mechanisms [131]. For instance, a study of 80 phaC genes found that 76 belonged to Class I and four to Class II, illustrating the diversity of PHA synthases among different microbial strains. Regulatory genes like phaR play a critical role in controlling PHA synthesis. In *Cupriavidus necator*, phaR acts as a transcriptional regulator, influencing

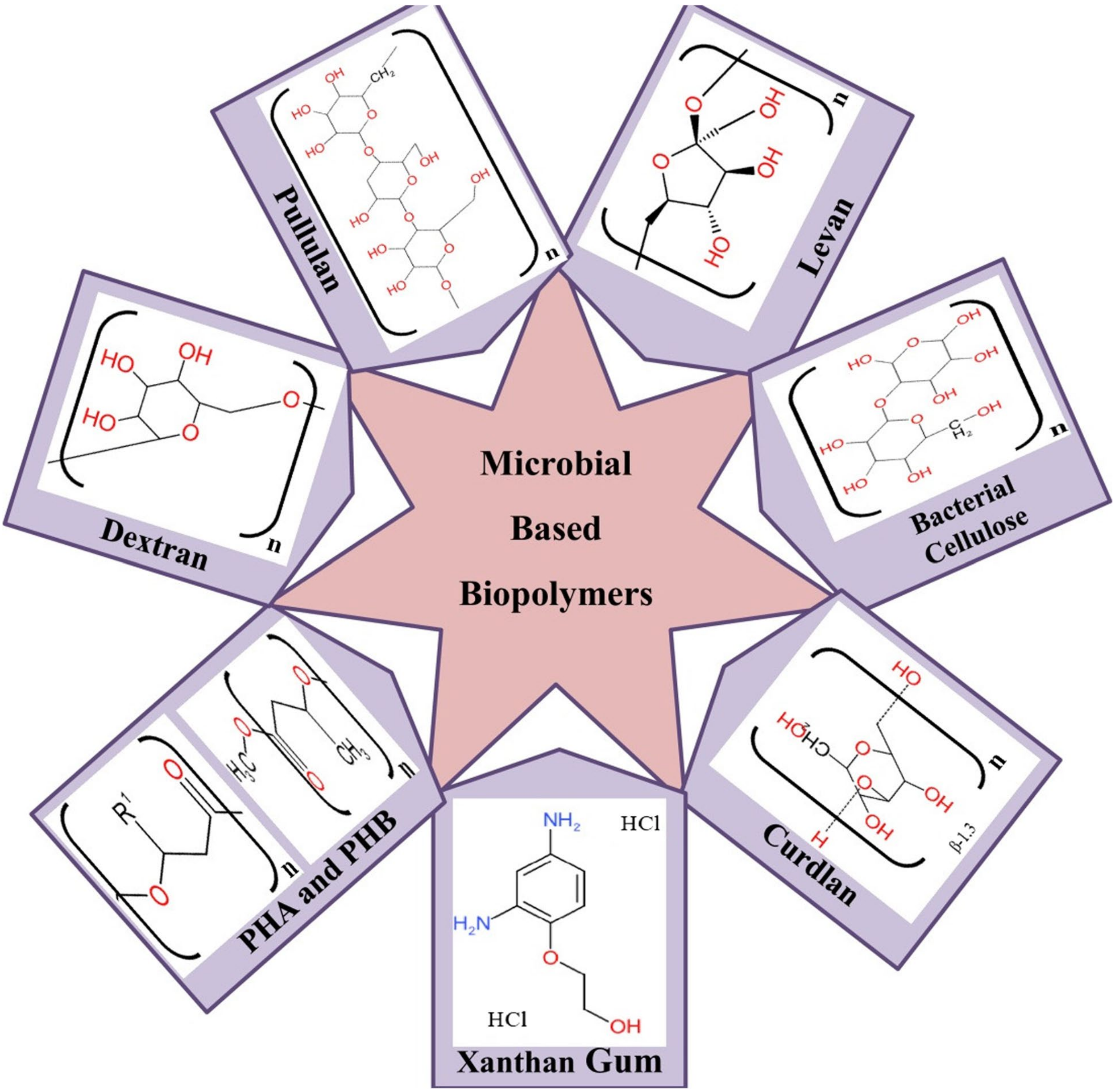


Fig. 2 Microbial-based biopolymers

the expression of phaC and other related genes. The deletion of phaR has been shown to decrease PHA yields, underscoring its significance in the regulatory network governing PHA production [71].

Ralstonia eutropha and *Bacillus megaterium* are model bacteria for isolation of these biopolymers [7]. *Schelegelella thermodepolymerans* DSM 15344 is a thermophilic bacterium was reported to transform different sugars into PHA optimally at 55 °C with maximum intake rate of xylose in comparison to other sugars [53]. They are extensively used as biocontrol agents, drug carriers, biodegradable implants, memory enhancers, and anticancer agents [100].

Xanthan gum

It is polysaccharide obtained from gram negative aerobic bacterium *Xanthomonas campestris* [97], through aerobic fermentation of sugars. It constitutes an anionic complex carbohydrate consisting of pyruvylated mannose, D-uronic acid, 1,4-bonded glucan, 6-O-acetyl D-mannose and D-mannose. Its chemical composition is characterized by a linear chain of 1,4-linked β-D glucose serving as the backbone, with two trisaccharide units branching off at each glucose residue. Additionally, another side chain is formed by a linkage between two D-mannose and one D-glucuronic acid molecule. Xanthan shows shear reducing property i.e. pseudoplasticity and forms a viscous hydrogel when combined with water as water molecules get absorbed by hydrogen bonds that forms xanthan gum [69]. It serves as an emulsifier, stabilizer, thickening and gelling agent in pharmaceutical and cosmetics industries. Furthermore, it can make conjugates with other polymers [7].

Extraction and purification techniques for bio-based polymers

Extraction techniques of biopolymers are different in accordance to their structural complexity (Table 3). For example – Lignocellulose, composed of monomers units of cellulose, hemicellulose, and lignin. It cannot easily digested because of presence of covalent bonding between phenolic groups and carbohydrates in its wall structure. Extraction of lignin, cellulose and hemicellulose can be done by supercritical fluid extraction method, microwave assisted and non- thermal plasma methods [64, 107]. These are eco-friendly techniques of extraction.

a) **Extraction of plant based biopolymers** Plant cell wall is rigid and complex. Therefore, extraction methods are harsh as compare to microbial cells. Mechanical extraction, Enzyme- assisted extraction, microwave assisted extraction and supercritical fluid extractions are various methods for extraction of biobased polymers from plants (Table 3). Examples: Cellulose extraction by alkali treatment, bleaching, and acid hydrolysis. Starch extraction by wet milling and dry milling followed by centrifugation, and drying.
b) **Extraction of microbial based biopolymers** Biopolymers extraction methods are different for intracellular and extracellular biopolymers (Table 3). For intracellular biopolymers, lysozymes are used to treat microbial cells followed by extraction of organic solvent on the basis of solubility and insolubility of biopolymer. EDTA- microwave assisted and natural deep eutectic solvents (NADESs) are to widely accepted methods for extraction of microbial biopolymers. Poly (3-hydroxybutyrate) is an intracellular biopolymers and it is extracted from *Pseudomonas putida* by deep eutectic solvents.

Purification techniques

To reduce content of impurities from extracted biopolymers various processes can be adopted based on their solubility, including adsorption, chromatography, membrane separation and precipitation (Table 4). However, precipitation using isopropanol and Fehling solution led to high yield of biopolymer and reduce protein fraction, respectively [9]. Purifying biopolymers involves distinct challenges, benefits, and constraints that are essential to their successful application across industries such as food, medicine, and manufacturing.

Advantages of biopolymer purification

1. Sustainability: Biopolymers are produced from renewable biological sources, offering an eco-friendly alternative to traditional plastics. Their ability to biodegrade helps in minimizing plastic waste and pollution [16].
2. Biocompatibility: Numerous biopolymers demonstrate outstanding compatibility with biological systems, making them ideal for medical uses such as drug delivery systems and tissue engineering. This characteristic is essential for applications involving interactions with biological tissues [45].
3. Functional Versatility: Biopolymers can be tailored to exhibit particular attributes, including improved mechanical strength, thermal stability, and barrier properties. This flexibility enables their application across a wide range of fields, from packaging to biomedical devices [45].

Challenges in biopolymer in purification

1. Extraction Challenges: Extracting biopolymers from natural sources can be intricate and expensive, often requiring several stages, such as purification and modification. This process can result in low yields and elevated production costs [1].
2. Reduced Mechanical Properties: Biopolymers typically have weaker mechanical properties, such as lower tensile strength and flexibility, compared to synthetic polymers. This drawback requires continued research to improve their performance for practical use [1, 45].
3. Processing Requirements: Biopolymers often need particular processing conditions to preserve their properties, adding complexity to their purification and use. For example, they can be sensitive to temperature and humidity, which impacts their stability and practicality [12].

Limitations of biopolymer purification

1. Bioavailability Issues: Processing Requirements: Biopolymers often need particular processing conditions to preserve their properties, adding complexity to their purification and use. For example, they can be sensitive to temperature and humidity, which impacts their stability and practicality [86].
2. Cost-Effectiveness: Purifying biopolymers can be costly and time-intensive, which may reduce their competitiveness against conventional synthetic polymers. This economic factor presents a major obstacle to their broader adoption [45].

Application of biopolymers

Biopolymers are being used in various industries because of their sustainable nature and biodegradability. Microbial and plant based biopolymers have similar and competing properties with conventional polymers. These biopolymers are fulfilling numerous needs of industries such as PLA and PHA highly used for packaging purposes. Although, mechanical, barrier and tensile strength of conventional polymers is higher as compare to biopolymers. But by different modifications such as etherification esterification and copolymerization properties of biopolymers can be tailored. For example, Polylactic acid high tensile strength but low toughness, however mixing of PLA with polyhydroxyalkanoates (PHA) can increase toughness [74]. Similarly, barrier property of bio-based polymers can be enhanced by nanotechnology and surface coating to make them suitable for packaging purposes [98]. Therefore, biopolymers are replacing synthetic polymers and limiting dependence of industries on fossil fuels. Their toxicity is very low as compare to synthetic polymers so it is highly used in biomedical industries and ensures safety concerns. These biopolymers are replacing synthetic polymers due to their remarkable performance and cost effectiveness (Fig. 3, Tables 1 and 2).

Medical and biomedical applications

Biopolymers have garnered significant attention in the medical and biomedical fields due to their biocompatibility, biodegradability, and versatility. These naturally derived materials offer a sustainable alternative to synthetic polymers, making them ideal for a wide range of

Table 3 Techniques employed for the extraction of biopolymers

Extraction Techniques	Principle	References
Mechanical Extraction	It employs physical methods like grinding and pressing to release polymers from plant cells or microbial biomass	Jha and Kumar 2019 [51]
Enzyme-Assisted Extraction	Enzymes such as cellulose and lysozymes used to break down plant cell walls or microbial membranes, respectively. It leads to release of polymers	Nadar et al. 2018 [81]
Microwave Assisted Extraction	Microwave radiation is used as heat source to disrupt cell wall	Mandal et al. 2007 [64]
Non-thermal plasma	It is a pre-treatment technique in which partial voltage discharged to rise temperature of electron leads in reduction of recalcitrant nature of any hard material such as lignocellulosic material	Pereira et al. 2021 [91]
Supercritical Fluid Extraction	Pressured carbon dioxide used to extract polymers from plant biomass or microbial cultures	Sapkale et al. 2010 [107]
Deep eutectic solvents	Mixture of green solvents liked with hydrogen bonds with low toxicity and used to lower melting point of any mixture	Didion et al. 2024 [29]

Table 4 Techniques employed for the purification of biopolymers

Purification techniques	Principle	Reference
Adsorption	It is surface based phenomena in which biopolymers bind with surface of adsorbent	Agbovi and Wilson 2021 [6]
Chromatography	It is a separation technique based on partial adsorption principle, in which chemical mixture can be transported through mobile phase and molecules can be separated on stationary phase on the basis of differential distribution of solute	Baidurah 2022 [14]
Membrane separation	Different membrane separation techniques such as ultrafiltration, microfiltration, nanofiltration, elctrodialysis and gas filtration. These techniques are classified according to membrane pore size	Lin et al. 2023 [61]
Precipitation/ Selective Dissolution	It is based on the solubility of biopolymer in a specific solvent and impurities can be removed. Barium hydroxide, Fehling solution and isopropanol etc. are different solvents being used for precipitation process	Amid and Mirhosseini 2012 [9]

applications, from drug delivery systems to tissue engineering. Their ability to interact with biological systems without eliciting adverse immune responses has made biopolymers a cornerstone in the development of innovative medical technologies. As the demand for safer and more effective medical treatments continues to grow, biopolymers are emerging as crucial components in advancing healthcare solutions.

Below is an overview of the diverse applications of biopolymers within the medical and biomedical industries:

1. Wound healing and tissue engineering
Biopolymers like collagen, alginate, and fibrin play a significant role in wound healing applications. Collagen is commonly applied as a surface coating on tissue culture plates and is also used in basic gels for cell culture. Alginate finds its use in regenerative medicine and tissue engineering. Fibrin functions as a hemostatic agent and surgical adhesive, aiding in blood clotting and accelerating the wound healing process [16].
2. Drug delivery systems
Biopolymers are being increasingly utilized in drug delivery systems due to their ability to encapsulate therapeutic agents and enable controlled release. Notable examples include polyhydroxyalkanoates (PHAs) and chitosan, which are used to deliver small molecules and proteins. Recent studies have focused on creating transdermal patches and nanoparticles from biopolymers for targeted drug delivery, which improves bioavailability and therapeutic effectiveness [35, 38].
3. Nanofiber applications
Biopolymer nanofibers, like those derived from silk fibroin and gelatin, are employed in a range of medical applications, including antimicrobial agents, biosensors, and tissue engineering scaffolds. Their large surface area and porosity are well-suited for enhancing cell adhesion and proliferation, which are essential for effective tissue regeneration [50].
4. Implantable devices
Biopolymers are being increasingly incorporated into the development of implantable medical devices because of their compatibility with human tissues and low risk of immunogenicity. Materials such as polylactic acid (PLA) have been used in sutures and surgical meshes, offering support for damaged tissues while promoting healing and minimizing the risk of infection [15, 18].
5. Biodegradable packaging for pharmaceuticals
Biopolymers are also used in pharmaceutical packaging, safeguarding drugs and surgical instruments from contamination while maintaining their safety and effectiveness. Their biodegradable nature aligns with the increasing demand for sustainable materials in the healthcare industry. Natural polymers such as starch, alginate, and cellulose derivatives serve as fillers to increase tablet mass and act as binders to enhance particle cohesion during compression. Several biodegradable polymers, including poly(glycolic acid), poly(lactic acid) as well as poly(ε-caprolactone), have been tested for controlled release applications [38, 47, 93].
6. Regenerative medicine
In regenerative medicine, biopolymers act as scaffolds that replicate the extracellular matrix, providing a conducive environment for cell growth and tissue repair. Advanced techniques, such as 3D printing, have enabled the fabrication of intricate structures with biopolymers like alginate, starch, chitosan and PLA, which can be customized for specific tissue engineering needs [35].
7. Antiviral and antibacterial application
Recent research has emphasized the potential of specific biopolymers, like curdlan and xanthan gum, as effective antiviral and antibacterial agents. These characteristics make them well-suited for use in wound dressings and other medical devices where controlling infections are crucial [16].

Additionally, Starch is used in bone, spinal cord treatment and cartilage regeneration due to its adhesive nature. Agarose hydrogels facilitate cell adhesion and thus used in tissue regeneration, kindey and fibroblast encapsulation. Alginate, chitosan and carrageenan used as regenerative medicines and for tissue engineering [130]. Chitosan is mainly used in implants of ligaments, cartilage, bone, tendon, nerve, stent, liver and skin regeneration. Likewise, PHAs plays important role drug delivery system [33]. Adhesion, contact inhibition, occlusion, covering, fixing and suturing are medicinal applications of various biopolymers. For example- PLA (Polylactic acid) is a microbial biopolymer used for suturing [75, 127].

Role in food industry

Biopolymers play a significant role in the food industry due to their diverse functional properties and sustainability. They are utilized in various applications, including food packaging, where they enhance product shelf life and reduce environmental impact. Additionally, biopolymers serve as thickeners, stabilizers, and gelling

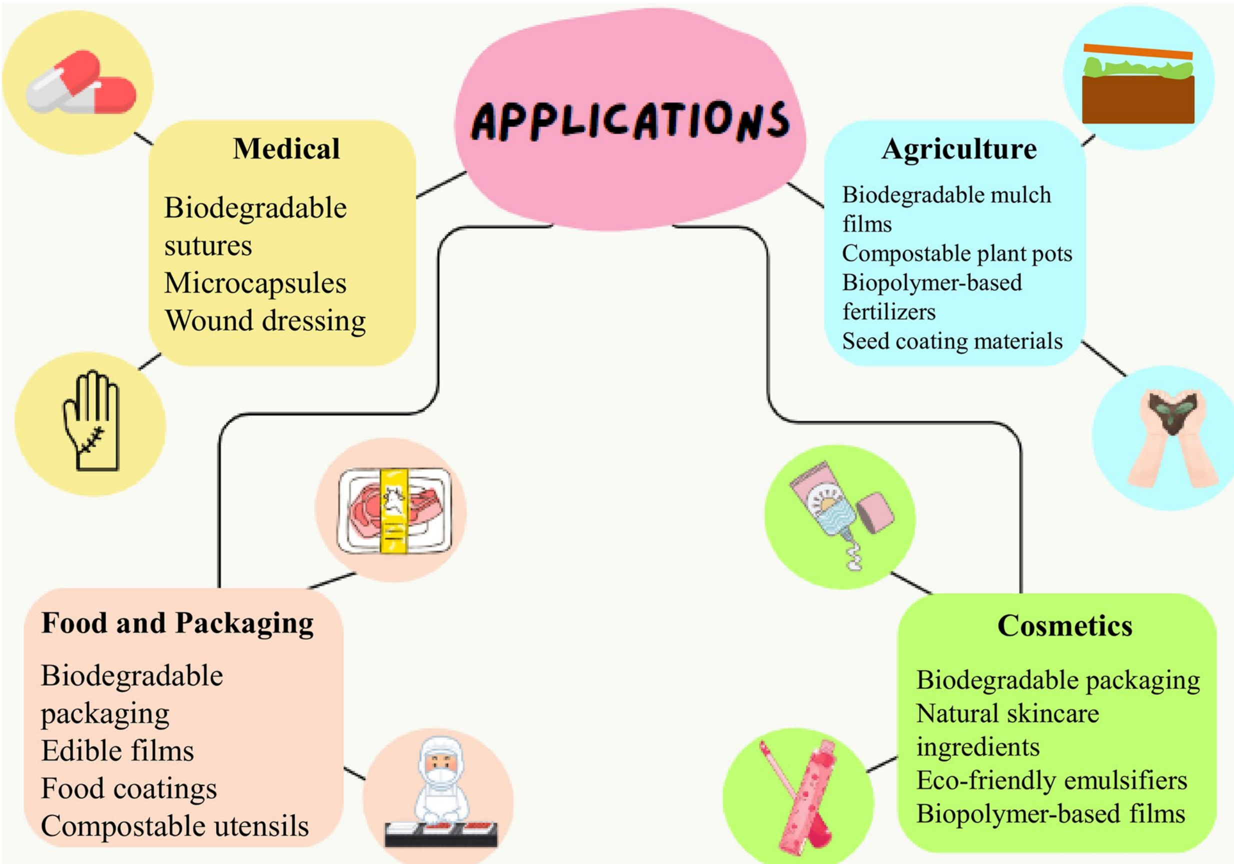


Fig. 3 Applications of biopolymers in different sectors

agents in food formulations, contributing to improved texture and consistency. Their natural origin and biodegradability align with the growing consumer demand for eco-friendly and health-conscious food products. Key developments include:

1. Food packaging

• Protein-based films
Recent advancements in protein-based biopolymers have led to the creation of sustainable food packaging materials. These films are designed to be biodegradable and can effectively replace traditional plastic packaging, reducing environmental impact [17]. For example- whey protein based films are widely being used for packaging purposes as it has excellent barrier properties and it is biocompatible material [101].
• Biodegradable films
A variety of biodegradable films made from materials like chitosan, cellulose, and alginate have been developed. These films not only serve as packaging but also help in extending the shelf life of food products by providing barriers against moisture and oxygen [5].
• Active and intelligent packing
Biopolymers are increasingly used in active packaging systems designed to interact with food products for better preservation. For example, films embedded with antimicrobial agents can prevent the growth of spoilage organisms, thus enhancing food safety [16, 40].

2. Edible films and coatings
Biopolymers are also utilized in the production of edible films and coatings, which serve multiple purposes.

• Encapsulation of bioactive compounds
Edible coatings made from biopolymers can encapsulate nutrients and bioactive compounds, enhancing the nutritional profile of food products while also providing a protective barrier [20].
• Improved texture and stability

The use of polysaccharides and proteins in food formulations can improve texture and stability, making them essential in the design of new food products [96].

Role of biopolymers in agriculture

Biopolymers are making significant strides in agriculture due to their versatile applications and eco-friendly nature. They are utilized in various ways, including soil conditioning, where they enhance soil structure and water retention. Additionally, biopolymers serve as controlled-release carriers for fertilizers and pesticides, ensuring more efficient nutrient delivery and reduced environmental impact. Their biodegradable properties contribute to sustainable agricultural practices by minimizing waste and improving soil health. The following provides a comprehensive overview of the applications of biopolymers in agriculture.

1. Biopolymer-based hydrogels Biopolymer-based hydrogels are three-dimensional networks capable of retaining substantial amounts of water, making them effective for soil conditioning. Their applications include:

- Water Retention: Hydrogels enhance soil moisture retention, which reduces the need for frequent irrigation and improves water use efficiency, especially in arid regions where water is scarce [60].
- Nutrient Release: They act as carriers for fertilizers and agrochemicals, providing controlled release and minimizing nutrient leaching. This improves nutrient availability for plants and lessens environmental impact [126].
- Soil Structure Improvement: Hydrogels enhance soil structure and aeration, fostering root development and overall plant health. Research shows that hydrogel interaction with various plant species can significantly influence crop productivity [124].

2. Biodegradable films, capsules and coatings

Biopolymers are utilized in the production of biodegradable films and coatings that safeguard crops and promote their growth:

- Seed Coatings: Biopolymer-based coatings can be applied to seeds to shield them from pests and diseases while delivering essential nutrients during germination, leading to enhanced seedling vigour and establishment [67].
- Mulching Films: Biodegradable mulching films made from biopolymers help suppress weed growth, retain soil moisture, and regulate soil temperature, thereby improving crop yields and reducing the need for chemical herbicides [70].
- Biopolymer capsules: Various types of plant and microbial biopolymers are used as carrier for encapsulation of microbial cell. Inoculation of encapsulated microbial cell in soil enhances their survival and makes them ideal to deal with various abiotic stresses [105]. For example, alginate, chitosan and gum arabic are used for encapsulation of *Bacillus cereus*, *Streptomyces fulvis* and *Trichoderma harzianum*, respectively [90].

Role of biopolymers in cosmetics

Cosmetic and personal care items are intricate blends designed for external application on the human body. Among their extensive ingredient lists are polymers, which can be either natural or synthetic [108]. Biopolymers are pivotal in the cosmetics industry, providing a sustainable and efficient substitute for conventional synthetic polymers:

- Advantages of Biopolymers in Skincare Products: Biopolymers such as PERFORMA™V, including variants like PERFORMA V-55 and V-150, blend plant-derived materials with synthetic waxes to deliver skin conditioning, moisturization, and non-greasy attributes in cosmetic formulas. They enhance features like lip gloss in lipsticks, enhance oil binding for solidity in stick applications, and promote smoothness in hair serums (https://chasecorp.com/nucerasolutions/understanding-the-real-benefits-of-biopolymers-in-skincare-products).
- The function of Biopolymers in Cosmetic Formulations: Biopolymers, derived from natural sources, are widely employed in cosmetics for their eco-friendliness and compatibility with the skin. PLA serves as packaging film for cosmetic items, while Micronized PLA or soy-derived biopolymers are utilized in exfoliating scrubs. Chitin, known for its antimicrobial properties, is employed as an active packaging material [125].
- Cosmetic Hydrogels: Biopolymers are employed to create hydrogels for cosmetic use. These hydrogels, derived from collagen, chitosan, hyaluronic acid, and various polysaccharides, provide advantages such as skin conditioning, hydration, and improved skin elasticity. However, certain biopolymers may pose drawbacks such as the risk of irritation or allergic reactions [72]

The versatility of biopolymers is attributed to their diverse sources, ranging from proteins (e.g., collagen, casein) and complex carbohydrates (e.g., cellulose, chitin) to polynucleotides (e.g., DNA, RNA).These biopolymers can be chemically or biologically synthesized, and their properties can be tailored through various processing techniques, such as solvent casting, graft copolymerization, 3D printing and electrospinning. The growing demand for sustainable and environmentally friendly materials has driven the development and application of biopolymers, which offer a promising solution to reduce the reliance on fossil-fuel-based polymers and mitigate the environmental impact of plastic waste. Conventional polymers are non- renewable energy resources with high carbon footprint and toxicity. Therefore, these concerns increase demand to replace petroleum-polymers with biopolymer for safer environment. However, feedstock availability is biggest concern in production of plant based biopolymers because of food and non-food competition and in case of microbial based biopolymers during scaling up of the product, aseptic and controlled conditions are required otherwise contamination can lead to production of undesired product.

Conclusion

In conclusion, biobased polymers derived from plants and microbes have demonstrated a promising avenue for sustainable material development across various industries, particularly in agriculture, medicine, and food packaging. The development of biodegradable films, hydrogels for soil conditioning, and biopolymer-based drug delivery systems represents significant advancements, all contributing to sustainability and a reduced environmental impact. The environmentally friendly nature of these biopolymers, coupled with their biodegradability and renewability, positions them as viable alternatives to traditional petroleum-based plastics. Despite these advancements, research should continue to focus on improving the mechanical properties and scalability of biopolymers, ensuring their broader adoption in industrial applications. Overall, the emerging domain of biobased polymers shows potential to foster innovation and sustainability across various industries, providing environmentally friendly answers to global issues.

Future perspective

The aim of this review is to address countless benefits and limitation or gap in knowledge about incorporation of biobased polymers in various industries. One major limitation is scaling up of microbial based biopolymers because it should be operated into aseptic conditions which are very costly and minor mistake can lead to production of undesirable product. Additionally, mechanical and thermal properties of biopolymers should be improved with more alternative techniques as these often lag behind conventional plastic. Mechanism of biodegradation of biopolymers and their end product should be studied into detail. By addressing more application, the usage of biopolymers can be increased. The future of biopolymers appears highly promising, fueled by technological advancements, sustainability objectives, and the growing demand for eco-friendly materials. Recent research underscores several key areas where biopolymers are anticipated to make substantial impacts across various sectors. They are increasingly recognized for their potential to replace traditional petroleum-based plastics, addressing concerns related to plastic pollution. The emphasis on biodegradable and compostable materials is expected to intensify, with biopolymers derived from renewable resources becoming more prevalent in packaging, agriculture, and consumer products. Innovations in biopolymer-based packaging aim to reduce waste while ensuring food safety and quality, though scaling up production at competitive costs remains a challenge.

Advancements in biopolymer technology are also notable. The integration of nanomaterials into biopolymers is being explored to enhance their mechanical and barrier properties, potentially leading to smart packaging that responds to environmental changes. Additionally, hybrid materials combining biopolymers with synthetic polymers are showing promise for applications in food packaging and medical devices, offering improved performance while maintaining biodegradability. In the medical field, biopolymers are poised to revolutionize drug delivery systems, tissue engineering, and implantable devices due to their biocompatibility and biodegradability. Research focuses on developing biopolymer scaffolds that support cell growth and regeneration, potentially advancing regenerative medicine. In the food industry, biopolymers are being used to create edible films and coatings that improve food preservation and safety, with intelligent packaging systems monitoring food quality in real-time emerging as a key area of interest.

For biopolymers to achieve widespread adoption, economic viability is crucial. Research is exploring the use of agricultural waste and by-products as feedstock to lower production costs and enhance sustainability. Collaboration between academia and industry is essential to bridge the gap between research and commercial application, with successful case studies encouraging investment and interest from manufacturers. In summary, the future of biopolymers is bright, with ongoing innovations expected to enhance their functionality and reduce costs. As environmental concerns drive the demand for sustainable materials, biopolymers are set to play a vital role in shaping a more sustainable future across packaging, medicine, and food technology. Continued research and development will be the key to overcoming current challenges and unlocking the full potential of biopolymers.

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Author details
[1]Department of Microbiology, College of Basic Sciences and Humanities, Punjab Agricultural University, Ludhiana, Punjab 141004, India.

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