Journal of
Polymer Materials

Tech Science Press

https://doi.org/10.32604/jpm.2026.075913

REVIEW

Biopolymer–Microbe Interactions: Emerging Biotechnological Strategies for Sustainable Materials and Therapeutics

Esam Bashir Yahya*

Department of Microbiology, Faculty of Science, Al-Asmarya Islamic University, Zliten, Libya

*Corresponding Author: Esam Bashir Yahya. Email: essam912013@gmail.com

Received: 11 November 2025; Accepted: 07 April 2026; Published: 30 June 2026

ABSTRACT: Biopolymer–microbe interactions have emerged as a central theme in the development of sustainable materials and next-generation therapeutic strategies. This work provides a critical and integrative analysis of recent advances in biopolymer-based systems designed to modulate microbial behavior, with particular emphasis on antimicrobial activity, biofilm regulation, and host–microbe compatibility. Unlike conventional reviews that primarily catalogue existing studies, this manuscript systematically evaluates the mechanistic foundations governing polymer–microbe interactions, highlighting how physicochemical properties such as surface chemistry, porosity, charge distribution, and biodegradability influence microbial adhesion, virulence, and resistance patterns. Recent experimental evidence demonstrates that rationally engineered biopolymers especially polysaccharide- and protein-based matrices—can selectively inhibit pathogenic microorganisms while preserving beneficial microbiota, offering a strategic advantage over traditional antimicrobial approaches. Furthermore, this review identifies key methodological limitations in current studies, including inconsistencies in microbial models and inadequate long-term performance evaluation, and outlines critical research gaps hindering clinical translation. By integrating material science, microbiology, and biotechnology perspectives, this work advances the field beyond descriptive frameworks and provides actionable insights for designing next-generation biopolymer platforms for sustainable materials and therapeutic applications.

KEYWORDS: Biopolymers; biopolymer-microbe interfaces; metabolic engineering; microbial synthesis synthetic biology

1 Introduction

Biopolymers have emerged as a cornerstone of modern biotechnology, offering a sustainable alternative to petroleum-based synthetic polymers [1]. Derived from renewable biological sources such as plants, animals, and microorganisms, biopolymers exhibit diverse structural and functional characteristics, including biodegradability, biocompatibility, and tunable physicochemical properties [2]. Their broad range of applications spans packaging [3], agriculture [4], biomedical engineering [5], pharmaceuticals [6], and environmental remediation [7]. Unlike conventional plastics, biopolymers can be integrated into circular economy frameworks, where their natural degradability reduces long-term ecological burden [8]. This makes them highly relevant at a time when concerns over plastic pollution, climate change, and sustainable resource utilization are at the forefront of global priorities.

Among various sources of biopolymers, microorganisms hold a distinctive position because of their capacity to synthesize structurally unique macromolecules under mild and controllable conditions [9].

Microbes produce a wide variety of extracellular and intracellular polymers, including polyhydroxyalkanoates (PHAs) [10], extracellular polysaccharides (EPS) [11], bacterial cellulose [12], and fungal chitosan derivatives [13]. These polymers often possess inherent biofunctionalities that synthetic polymers cannot easily replicate, such as antimicrobial activity, high affinity for metal ions, or enhanced tissue compatibility [14]. Furthermore, microbial metabolism can be tailored through genetic engineering and synthetic biology approaches, enabling scalable and efficient production of custom biopolymers [15]. Consequently, the study of biopolymer microbe interactions has attracted significant scientific interest as it provides a framework for designing new biomaterials while simultaneously addressing pressing sustainability and health challenges.

The interface between biopolymers and microbes is not restricted to production alone but also extends to their dynamic interactions in natural and engineered systems. Biopolymers provide structural scaffolds that influence microbial colonization, adhesion, and biofilm formation [16]. Microbial enzymes such as cellulases, chitinases, and laccases play vital roles in the biodegradation and transformation of biopolymers, completing the natural recycling loop of organic matter [17]. Understanding these interactions not only sheds light on microbial ecology but also offers strategies for leveraging microbial capabilities in waste valorization, pollutant removal, and the generation of high-value functional materials. Recent advances in biotechnology have significantly expanded the possibilities for harnessing biopolymer–microbe systems. Synthetic biology tools allow precise manipulation of microbial genomes, enabling the design of strains capable of overproducing targeted biopolymers with desired characteristics. While several reviews have focused on either microbial production of specific biopolymers or applications of individual materials, comprehensive analyses that bridge biopolymer–microbe interactions with emerging biotechnological strategies for both sustainable materials and therapeutic applications remain limited. This review fills that gap by systematically discussing how microbes synthesize, modify, and degrade biopolymers, examining the interfaces where biopolymers and microbes co-function in both natural and engineered environments, and highlighting the translational opportunities in green materials and healthcare. By integrating perspectives from microbiology, biotechnology, and materials science, this article aims to provide a holistic framework for future research directions, emphasizing how harnessing biopolymer–microbe interactions can pave the way for sustainable solutions and innovative therapeutics in the current century.

2 Microbial Roles in Biopolymer Production

Microorganisms play central roles in the biosynthesis of biopolymers, serving as natural factories capable of converting renewable substrates into structurally diverse macromolecules [9]. Unlike chemically synthesized polymers, microbially derived biopolymers are produced under mild conditions, are often biodegradable, and can exhibit unique functionalities such as antimicrobial activity, selective binding affinity, and immunomodulatory effects [18]. Their biosynthesis relies on enzymatic pathways encoded in microbial genomes, which can be manipulated through metabolic engineering to enhance yield, tailor composition, and generate novel structures [19]. Broadly, microbial biopolymer production can be divided into native synthesis, where organisms naturally accumulate or excrete polymers as part of their metabolism, and engineered production, where genetic modifications expand or optimize biosynthetic capacities.

2.1 Native Microbial Synthesis of Biopolymers

Native microbial synthesis refers to the inherent ability of microorganisms to produce biopolymers without the need for extensive genetic modifications. These polymers may serve as structural components, storage compounds, or protective matrices for microbial survival. Polyhydroxyalkanoates are intracellular polyesters synthesized by numerous bacteria as carbon and energy storage materials under nutrient-limited but carbon-rich conditions [1]. Over 150 monomeric units of PHAs have been identified, resulting in

polymers with highly variable thermal and mechanical properties [2]. Despite challenges related to high production cost, their native microbial origin offers unparalleled diversity and tunability. In a recent study, the authors optimized the production conditions for PHAs microbially synthesized biodegradable bioplastics that offer a sustainable alternative to petroleum-based plastics [3]. From 341 isolates obtained from composted soil, the most efficient producer was identified as *Ensifer adhaerens* HD34, exhibiting a PHA accumulation of 72.96% of cell dry weight. Using response surface methodology, the study determined optimal production parameters, including a medium containing potato dextrose broth and D-glucose at pH 9, cultured at 28°C for five days [3]. Comprehensive characterization using GC, NMR, FTIR, and XRD confirmed the polymer as PHB with excellent thermal stability, highlighting its potential for eco-friendly bioplastic production. Fig. 1 presents and illustration of microbial synthesis of biopolymers and the specific approach for production and extraction of PHA.

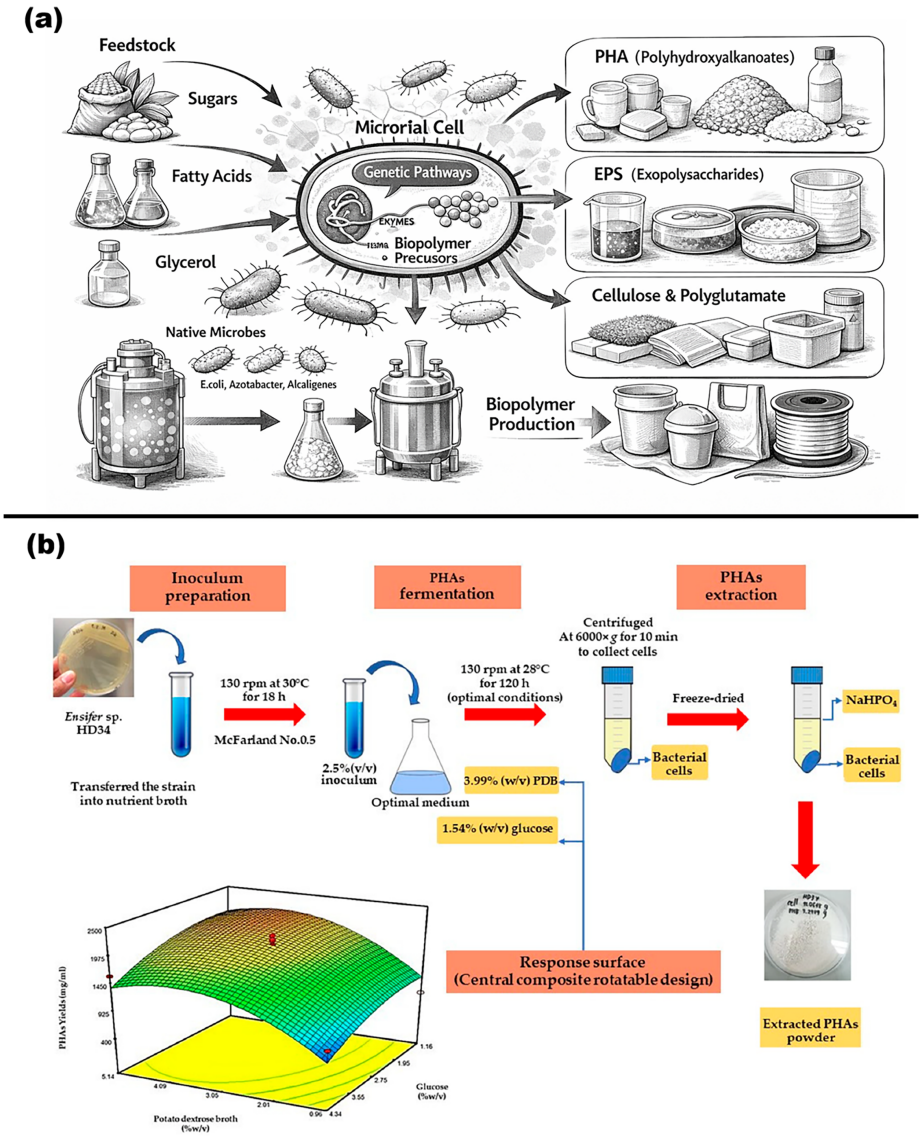

Figure 1: Schematic illustration of microbial synthesis of biopolymers from different bioresources (**a**) and the specific approach for production and extraction of PHA Adapted with permission from [3] (**b**).

Extracellular polysaccharides are secreted by a wide range of bacteria and fungi, playing critical roles in biofilm formation, cell adhesion, and protection against desiccation and immune responses [4]. Xanthan gum, produced by *Xanthomonas campestris*, and gellan gum from *Sphingomonas elodea* are industrially important EPS widely used as thickeners, stabilizers, and gelling agents in food and pharmaceutical formulations [5]. Similarly, levan, dextran, and pullulan represent diverse EPS with applications in medicine and material science [6]. Their production under natural conditions highlights the ecological importance of polysaccharides while offering scalable opportunities for commercial exploitation. Certain acetic acid bacteria, particularly *Komagataeibacter xylinus*, are prolific producers of bacterial cellulose (BC). BC is chemically identical to plant cellulose but possesses superior crystallinity, mechanical strength, and water-holding capacity [7]. Its nanoscale fibrillar network makes it highly attractive for biomedical applications such as wound dressings, tissue scaffolds, and artificial blood vessels [8]. Microalgae represent another important microbial source of biopolymers such as alginate, carrageenan, and agar [9]. Refer to Table 1 for the illustration of biopolymers and their microbial production.

Table 1: Illustration of biopolymer fabrication from different microorganisms.

Biopolymer	Category	Microorganism	Reference
Chitosan	Polysaccharide	*Roccella montagnei*	[10]
Polyhydroxyalkanoates	Polyester	*Bacillus megaterium*	[11]
Alginate	Polysaccharide	*Pseudomonas* spp.	[12]
Pullulan	Polysaccharide	*Aureobasidium pullulans*	[13]
Poly (γ-glutamic acid)	Polyamide	*B. licheniformis*	[14]
Hyaluronic acid	Polysaccharide	*Streptococcus zooepidemicus*	[15]
Polyhydroxyalkanoates	Polyester	*Chlorella minutissima*	[16]
β-glucan	Polysaccharide	*Aureobasidium thailandense*	[17]
Polylactide	Polyester	*Corallina elongata*	[18]

2.2 Genetic and Metabolic Engineering of Microbes for Enhanced Production

While native microbial systems naturally produce an array of biopolymers, their productivity, monomer composition, and scalability are often insufficient for industrial and therapeutic applications. To overcome these limitations, genetic and metabolic engineering approaches have been increasingly employed to redirect microbial metabolism, enhance flux toward biopolymer biosynthetic pathways, and introduce novel functionalities [19,20]. These strategies have transformed microorganisms into efficient cell factories, enabling the production of high-value polymers at commercially viable yields and with customizable properties [19]. *E. coli* and *Corynebacterium glutamicum* have been used as the primary microbial hosts for L-tryptophan biosynthesis, owing to their well-characterized metabolism and genetic tractability [21,22]. The L-tryptophan pathway in *E. coli* involves glycolysis, the pentose phosphate pathway, and the aromatic amino acid biosynthetic route, leading from glucose to chorismate and ultimately to L-tryptophan under operon regulation [23]. Metabolic engineering efforts have focused on eliminating feedback inhibition, disrupting competing pathways, and enhancing metabolic flux toward tryptophan synthesis [24]. Additionally, fermentation optimization plays a crucial role in maximizing yields and minimizing by-products [24]. Fig. 2 illustrates the strategies used in genetic and metabolic engineering to enhance microbial biopolymer production. Different engineering approaches, including DNA editing, CRISPR-Cas9–mediated genome modification, gene deletion, and metabolic pathway optimization, are applied to microbial cells to redesign their internal metabolic networks. These modifications improve precursor availability, regulate biosynthetic

pathways, and increase cellular efficiency. Complementary strategies such as metabolic modeling, synthetic biology tools, strain development, and adaptive laboratory evolution are integrated to optimize microbial performance. The engineered microbes are subsequently cultivated in bioreactors, resulting in enhanced yield and efficiency of bioproducts and final biomaterial products.

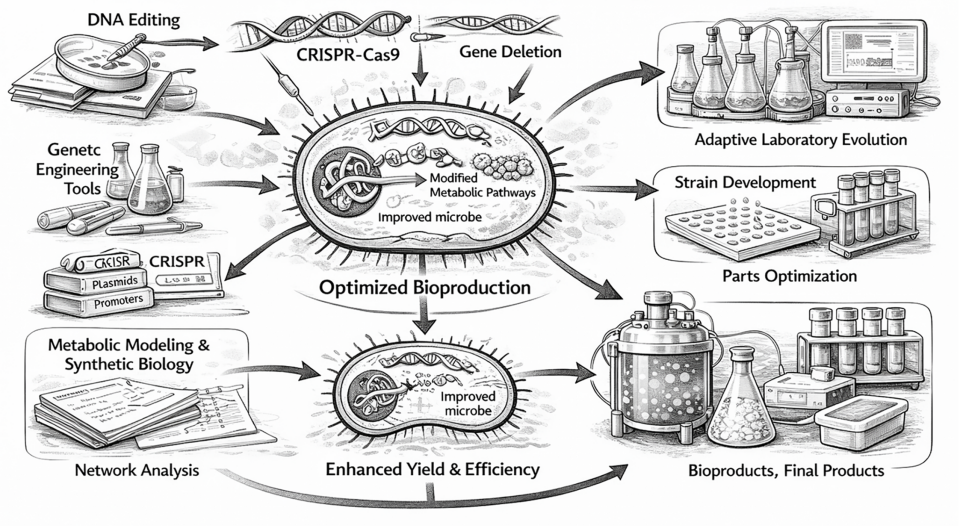

Figure 2: Schematic illustration of genetic and metabolic engineering strategies used to enhance microbial biopolymer production, including genome editing, metabolic pathway optimization, strain development, and bioprocess cultivation leading to improved yield and efficiency.

Metabolic engineering involves the targeted manipulation of enzymatic pathways to increase precursor availability, in one study, the production of polyhydroxyalkanoate, precursors such as acetyl-CoA, propionyl-CoA, or 3-hydroxybutyryl-CoA are essential for polymer chain elongation [25]. Overexpression of acetyl-CoA synthetase or deletion of competing pathways (e.g., acetate excretion) in *Cupriavidus necator* and *Escherichia coli* has been shown to increase PHA yield significantly [25]. Similarly, in bacterial cellulose production, overexpression of cellulose synthase genes (bcsA–D operon) in Komagataeibacter strains increases cellulose crystallinity and fibril density, thereby enhancing mechanical strength and water-holding capacity [26]. Flux balance analysis and constraint-based modeling are now routinely applied to predict optimal engineering targets [27]. Redirecting central carbon metabolism from glycolysis to the pentose phosphate pathway can improve NADPH supply, which is critical for biosynthetic reactions such as fatty acid-derived polymer precursors. These approaches illustrate how systemic metabolic rewiring allows for higher titers and improved material properties. Despite remarkable progress, several challenges hinder the full realization of engineered microbial systems. Metabolic burden and toxicity associated with high polymer accumulation often reduce host fitness, limiting scalability [28]. Balancing metabolic fluxes in complex pathways remains a technical hurdle, particularly when multiple cofactors and regulatory networks are involved [29]. Finally, regulatory and biosafety concerns associated with genetically modified organisms may restrict industrial deployment, particularly in food and therapeutic sectors.

3 Biopolymer–Microbe Interfaces

The interface between biopolymers and microbes is a dynamic and multifaceted domain that underpins both natural processes and engineered applications. Biopolymers often provide structural scaffolds that support microbial adhesion, colonization, and biofilm formation, while microbes, in turn, contribute to

the modification, degradation, and functionalization of these materials [30]. Recent advances in high-resolution imaging, surface characterization, and omics technologies have deepened insights into how microbes recognize, interact with, and transform biopolymer surfaces. This knowledge is increasingly being applied to engineer living materials, functional biointerfaces, and adaptive therapeutic systems.

3.1 Structural and Functional Interactions (Adhesion, Colonization, Degradation)

Microbial adhesion represents the first step in biopolymer–microbe interaction [31]. Adhesion occurs through non-specific physicochemical forces (e.g., van der Waals, electrostatic, and hydrophobic interactions) as well as specific molecular recognition mechanisms [32]. For instance, bacterial adhesins, fimbriae, and extracellular proteins interact directly with functional groups on biopolymer surfaces such as hydroxyl, amine, or carboxyl moieties [33]. Fungal adhesion, by contrast, often involves hydrophobic proteins like hydrophobins, which facilitate attachment to both hydrophobic and hydrophilic biopolymer matrices [34,35]. The surface properties of the biopolymer including roughness, porosity, crystallinity, and charge strongly influence microbial adhesion. Bacterial cellulose's nanofibrillar network was found to promotes dense microbial colonization, making it a favorable scaffold for probiotic encapsulation [36]. Conversely, highly crystalline chitosan surfaces exhibit antimicrobial activity due to their polycationic nature, which disrupts bacterial membranes, thereby reducing adhesion [37].

Following adhesion, microbes often transition into biofilm-forming states, creating complex, structured communities embedded within extracellular polymeric substances [38]. It has been reported that biopolymers can both support and modulate biofilm development; alginate is not only produced by *Pseudomonas aeruginosa* as a biofilm matrix component but also serves as a substrate that supports colonization by diverse microbial consortia [39]. Biopolymer scaffolds used in biomedical implants, such as hydrogels or aerogels, are similarly susceptible to microbial colonization, which can be beneficial (as in probiotic delivery systems) or detrimental (as in implant-associated infections) [40]. Advanced imaging studies have revealed that colonization often occurs preferentially along pores, fibrils, or defects within the biopolymer network. In mucoid bacterial strains, such as the cystic fibrosis isolate *P. aeruginosa* FRD1, alginate is secreted as a free, non-covalently attached polymer into the extracellular environment [41]. This overproduction leads to highly viscous colonies on agar, which atomic force microscopy reveals as a dense, gelatinous structure enveloping the cells (Fig. 3A). Beyond alginate, *P. aeruginosa* produces other key polysaccharides. The Psl polysaccharide, with a repeating pentasaccharide structure of D-mannose, L-rhamnose, and D-glucose, exhibits a helical distribution around the cell surface of strain PAO1 [42,43]. This arrangement, visualized through lectin staining, facilitates critical cell-cell and cell-surface interactions during biofilm development [44]. Further evidence from confocal microscopy suggests that Psl creates a fabric-like matrix that connects individual cells within the biofilm (Fig. 3B). In contrast, the precise structure of the Pel polysaccharide remains unconfirmed, though it is proposed to be a glucose-rich polymer distinct from cellulose [45]. Scanning electron microscopy of *P. aeruginosa* PA14 pellicles reveals an intercellular connecting matrix, which is likely composed of Pel but may also incorporate other polymers like LPS O-antigen and cyclic glucans (Fig. 3C) [46]. The presence of subpopulations producing different polysaccharides is a common feature in environmental and CF biofilms, often associated with the Rugose Small Colony Variant phenotype. This diversification is hypothesized to be a key survival strategy, enhancing the biofilm community's overall resilience to fluctuating environmental conditions.

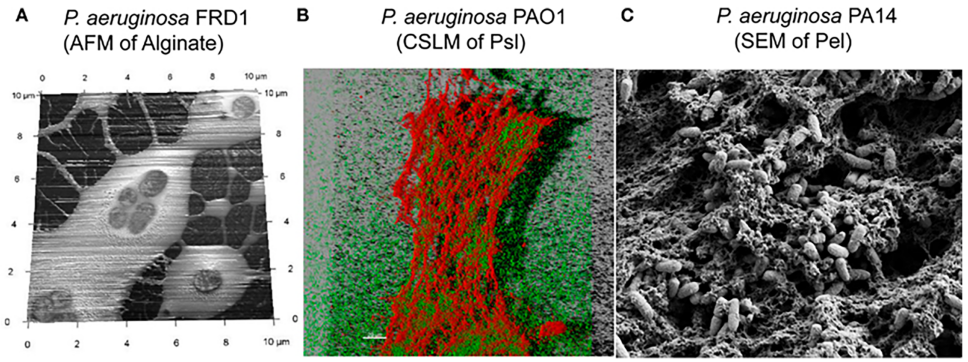

Figure 3: Visualization of *Pseudomonas aeruginosa* extracellular polysaccharides using multiple imaging techniques. (**A**) Atomic Force Microscopy (AFM) of strain FRD1 reveals alginate as a soft, loosely attached polymer encasing the bacterial cells. (**B**) Confocal Laser Scanning Microscopy (CLSM) of hydrated PAO1 pellicles displays a 3D reconstruction, with cells expressing green fluorescent protein and the Psl polysaccharide stained with CellMask Orange. (**C**) Scanning Electron Microscopy (SEM) of PA14 pellicles illustrates the fibrous extracellular matrix containing Pel, forming a network that embeds and links cells at the air–liquid interface. Adapted with permission from [47].

3.2 Microbe-Assisted Modification and Functionalization of Biopolymers

Microbes naturally degrade and utilize biopolymers; they can also be harnessed as biological tools for modifying and functionalizing polymer matrices [48]. These modifications often enhance the physicochemical properties, biocompatibility, or functional activity of biopolymers, broadening their applicability in biotechnology, medicine, and environmental science. Microbial enzymes are highly specific catalysts that enable site-directed modification of biopolymers under mild, environmentally friendly conditions [49]. Laccases and peroxidases secreted by fungi are widely used to graft functional groups onto polysaccharides, imparting antioxidant, antimicrobial, or crosslinking properties [50]. Similarly, microbial transglutaminases catalyze covalent crosslinking of proteins such as gelatin or casein, enhancing mechanical stability and resistance to enzymatic degradation [51]. Certain microbes are capable of depositing inorganic minerals within or on the surfaces of biopolymer matrices, resulting in hybrid organic–inorganic materials [52]. For instance, biomineralizing bacteria can induce calcium carbonate or hydroxyapatite deposition onto chitosan or collagen scaffolds, producing composites that mimic bone tissue [53,54]. These microbe-assisted mineralization processes are being explored for orthopedic implants, dental restorations, and bone grafts [55,56]. Similarly, microbial processes can be used to incorporate magnetic nanoparticles, conductive polymers, or metallic nanostructures into biopolymer matrices, creating multifunctional composites with applications in biosensing, catalysis, and environmental remediation [57].

4 Biotechnological Strategies and Tools

Harnessing biopolymer–microbe systems for sustainable materials and therapeutics requires more than relying on natural biosynthetic capacities. Modern biotechnology offers an expansive toolkit for engineering, processing, and scaling microbial systems to achieve enhanced yield, functionality, and industrial feasibility [58]. Among these, synthetic biology, enzyme-mediated biocatalysis, and fermentation technologies are particularly impactful. Together, they provide complementary strategies that bridge laboratory discovery with large-scale application.

4.1 Synthetic Biology Approaches

Synthetic biology enables the design of microbes with reprogrammed metabolic pathways and novel genetic circuits, allowing the biosynthesis of non-natural or highly customized biopolymers [59]. This goes beyond traditional metabolic engineering by enabling modular and programmable design of whole biosynthetic systems. Artificial operons encoding polyhydroxyalkanoate (PHA) synthases and precursor-supplying enzymes have been introduced into *E. coli* to produce copolymers with tunable mechanical and thermal properties [60,61]. A key innovation in synthetic biology is the development of standardized biological parts promoters, ribosome binding sites, coding sequences, and terminators that can be assembled into modular pathways [62]. These synthetic modules can be introduced into "chassis organisms" such as *E. coli*, *Saccharomyces cerevisiae*, or non-conventional hosts like *Corynebacterium glutamicum*. Minimal genome chassis strains are especially attractive, as they reduce background metabolic noise and improve flux control toward polymer biosynthesis [63]. Synthetic gene circuits can incorporate biosensors that respond to intracellular metabolites or environmental signals, enabling dynamic control of biopolymer synthesis [64]. For instance, sensors for acetyl-CoA levels can regulate PHA pathway genes in real time, ensuring optimal precursor utilization [65]. Similarly, optogenetic systems allow light-controlled polymer biosynthesis, offering spatiotemporal precision in regulating microbial productivity [66]. Synthetic biology also facilitates the incorporation of non-natural monomers into biopolymer chains, generating novel functionalities. Engineered microbial strains have been developed to polymerize lactate, glycolate, or aromatic compounds into biopolymer backbones, yielding materials with unique optical, mechanical, or bioactive properties [19,67]. Such designer polymers open new avenues in biomedical devices, smart packaging, and responsive materials.

4.2 Enzyme-Mediated Processing and Biocatalysis

Microbial enzymes are natural catalysts for polymer synthesis, modification, and degradation. Harnessing these enzymes in isolated or recombinant form provides precise control over polymer architecture, functional group placement, and post-synthesis modifications [68]. Enzymatic processing is environmentally friendly, as it occurs under mild conditions and avoids toxic reagents often associated with chemical modification [69]. Key examples include microbial glycosyltransferases, which catalyze the assembly of polysaccharides, and PHA synthases, which polymerize hydroxyacyl-CoA monomers [70]. Recombinant expression of these enzymes in cell-free systems has been explored to bypass metabolic burdens and achieve high-purity polymers [71]. Similarly, lipases and esterases have been employed for polyester synthesis, offering high selectivity and the ability to incorporate functionalized monomers [72]. Beyond synthesis, microbial enzymes facilitate biopolymer functionalization. Fungal laccases oxidize phenolic substrates, enabling grafting of antimicrobial or antioxidant moieties onto polysaccharides such as chitosan or alginate [73]. Transglutaminases are widely applied in protein crosslinking, enhancing mechanical stability of gelatin-based hydrogels and scaffolds [74]. These functionalizations significantly expand the scope of applications, particularly in medicine and food biotechnology. Microbial enzymes also underpin sustainable strategies for biopolymer recycling and circular bioeconomy. Enzymatic degradation of cellulose, starch, or chitin yields monomers that can be rechanneled into new biosynthetic processes [75]. This closed-loop biocatalysis reduces waste and promotes sustainability in polymer industries. Enzyme cocktails with synergistic activity (e.g., cellulase–xylanase blends) are increasingly optimized through protein engineering and directed evolution [76]. To enhance catalytic efficiency and substrate scope, microbial enzymes are frequently engineered through site-directed mutagenesis, rational design, or directed evolution [77]. For instance, engineered cutinases have been developed to degrade polyethylene terephthalate (PET), suggesting potential applications in hybrid polymer recycling [78]. Similarly, engineering PHA synthases has broadened

substrate specificity, enabling incorporation of diverse monomers [79]. Such tailored biocatalysts are vital for next-generation biopolymer processing.

5 Challenges and Future Perspectives

Despite remarkable advances in the synthesis, functionalization, and application of microbial biopolymers, several challenges persist that hinder their full integration into mainstream industrial, environmental, and biomedical sectors, and addressing these obstacles will be critical for shaping future trajectories. The first and perhaps most fundamental limitation is the economic feasibility of microbial biopolymer production, which remains significantly higher compared to petroleum-derived polymers due to the costs associated with feedstocks, fermentation infrastructure, and downstream purification [80]. Although low-cost substrates such as agricultural residues, food-processing by-products, and lignocellulosic biomass are increasingly being investigated, their complex composition, inhibitory by-products, and variability across seasons pose practical barriers that require robust pretreatment and microbial tolerance strategies, which in turn add to the overall process cost [81]. The scalability of fermentation processes is another major hurdle, as laboratory-scale successes often fail to translate directly into industrial-scale yields due to challenges in maintaining oxygen transfer, nutrient gradients, and microbial stability under high-cell-density conditions [82]. Moreover, the downstream recovery and purification of biopolymers, particularly intracellular products like polyhydroxyalkanoates, are energy-intensive and environmentally taxing when conventional solvent extraction methods are used, necessitating the development of greener, cost-effective separation methods such as enzymatic digestion, aqueous two-phase systems, or membrane technologies [83]. Beyond production costs, material performance limitations also constrain applications: many microbial polymers such as PHAs or alginates exhibit brittleness, thermal instability, or poor moisture resistance compared to synthetic plastics, requiring blending, composite formation, or functionalization, which can complicate processing and compromise biodegradability [84]. On the biomedical front, although microbial biopolymers exhibit promising biocompatibility, issues such as batch-to-batch variability, immunogenicity, sterilization stability, and long-term degradation kinetics remain insufficiently understood, raising concerns for regulatory approval and clinical translation [85]. Furthermore, while synthetic biology and genetic engineering have opened avenues for designer polymers and enhanced yields, biosafety concerns associated with genetically modified organisms remain a barrier to public acceptance and regulatory approval, especially for food-related and therapeutic applications, highlighting the urgent need for standardized risk assessment frameworks, containment strategies, and transparent communication with stakeholders [86]. Intellectual property issues also complicate commercialization, as patents on engineered strains, metabolic pathways, or specific biopolymer modifications can create monopolistic barriers, slowing innovation and technology transfer to developing regions where sustainable materials are most needed. Looking ahead, several concrete strategies can be leveraged to overcome existing challenges and accelerate the transition of microbial biopolymers into mainstream applications. One key direction is the advancement of synthetic biology and metabolic engineering to construct robust, high-yield microbial strains capable of producing biopolymers with controlled composition and functionality. In parallel, the implementation of cost-effective and sustainable production systems such as continuous fermentation, utilization of low-cost feedstocks, and waste valorization can significantly improve industrial scalability. Another promising approach lies in the development of hybrid and nanostructured biopolymer systems, where microbial polymers are combined with nanomaterials or chemically modified to enhance mechanical strength, stability, and application-specific performance. Additionally, the integration of computational tools, including machine learning and process modeling, can streamline strain design and optimize production parameters. Finally, establishing standardized processing protocols, clear regulatory pathways, and stronger industry academia partnerships will be essential to ensure reproducibility, safety,

and successful commercialization. Collectively, these strategies provide a practical and forward-looking roadmap for unlocking the full potential of microbial biopolymers across biomedical, environmental, and industrial sectors.

Acknowledgement: Not applicable.

Funding Statement: The author received no specific funding for this study.

Availability of Data and Materials: Not applicable.

Ethics Approval: Not applicable.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Koller M, Mukherjee A. Polyhydroxyalkanoates (PHAs)—production, properties, and biodegradation. In: Biodegradable polymers in the circular plastics economy. Hoboken, NJ, USA: Wiley; 2022. p. 145–204.
2. Naser AZ, Deiab I, Defersha F, Yang S. Expanding poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHAs) applications: a review on modifications and effects. Polymers. 2021;13(23):4271. doi:10.3390/polym13234271.
3. Khamkong T, Penkhrue W, Lumyong S. Optimization of production of polyhydroxyalkanoates (PHAs) from newly isolated *Ensifer* sp. strain HD34 by response surface methodology. Processes. 2022;10(8):1632. doi:10.3390/pr10081632.
4. Singh S, Datta S, Narayanan KB, Rajnish KN. Bacterial exo-polysaccharides in biofilms: role in antimicrobial resistance and treatments. J Genet Eng Biotechnol. 2021;19(1):140. doi:10.1186/s43141-021-00242-y.
5. Abdl Aali R, Al-Sahlany S. Gellan gum as a unique microbial polysaccharide: its characteristics, synthesis, and current application trends. Gels. 2024;10(3):183. doi:10.3390/gels10030183.
6. Ahuja V, Bhatt AK, Banu JR, Kumar V, Kumar G, Yang YH, et al. Microbial exopolysaccharide composites in biomedicine and healthcare: trends and advances. Polymers. 2023;15(7):1801. doi:10.3390/polym15071801.
7. Li W, Huang X, Liu H, Lian H, Xu B, Zhang W, et al. Improvement in bacterial cellulose production by co-culturing *Bacillus cereus* and *Komagataeibacter xylinus*. Carbohydr Polym. 2023;313(2):120892. doi:10.1016/j.carbpol.2023.120892.
8. Abdul Khalil HPS, Adnan AS, Yahya EB, Olaiya NG, Safrida S, Hossain MS, et al. A review on plant cellulose nanofibre-based aerogels for biomedical applications. Polymers. 2020;12(8):1759. doi:10.3390/polym12081759.
9. Madadi R, Maljaee H, Serafim LS, Ventura SPM. Microalgae as contributors to produce biopolymers. Mar Drugs. 2021;19(8):466. doi:10.3390/md19080466.
10. Logesh AR, Thillaimaharani KA, Sharmila K, Kalaiselvam M, Raffi SM. Production of chitosan from endolichenic fungi isolated from mangrove environment and its antagonistic activity. Asian Pac J Trop Biomed. 2012;2(2):140–3. doi:10.1016/s2221-1691(11)60208-6.
11. Mohapatra S, Pattnaik S, Maity S, Mohapatra S, Sharma S, Akhtar J, et al. Comparative analysis of PHAs production by *Bacillus megaterium* OUAT 016 under submerged and solid-state fermentation. Saudi J Biol Sci. 2020;27(5):1242–50. doi:10.1016/j.sjbs.2020.02.001.
12. Rehm BHA. Bacterial polymers: biosynthesis, modifications and applications. Nat Rev Microbiol. 2010;8(8):578–92. doi:10.1038/nrmicro2354.
13. Lin C, Zhang K, Zhao S, Wang W, Ru X, Song J, et al. Screening and identification of a strain of *Aureobasidium pullulans* and its application in potato starch industrial waste. Environ Res. 2022;214(5):113947. doi:10.1016/j.envres.2022.113947.
14. Kedia G, Hill D, Hill R, Radecka I. Production of poly-γ-glutamic acid by *Bacillus subtilis* and *Bacillus licheniformis* with different growth media. J Nanosci Nanotech. 2010;10(9):5926–34. doi:10.1166/jnn.2010.2614.
15. Kogan G, Šoltés L, Stern R, Gemeiner P. Hyaluronic acid: a natural biopolymer with a broad range of biomedical and industrial applications. Biotechnol Lett. 2007;29(1):17–25. doi:10.1007/s10529-006-9219-z.

16. Costa SS, Miranda AL, Andrade BB, de Jesus Assis D, Souza CO, de Morais MG, et al. Influence of nitrogen on growth, biomass composition, production, and properties of polyhydroxyalkanoates (PHAs) by microalgae. Int J Biol Macromol. 2018;116:552–62. doi:10.1016/j.ijbiomac.2018.05.064.
17. Kayanna N, Suppavorasatit I, Bankeeree W, Lotrakul P, Punnapayak H, Prasongsuk S. Production of prebiotic aubasidan-like β-glucan from *Aureobasidium thailandense* NRRL 58543 and its potential as a functional food additive in gummy jelly. LWT. 2022;163(3):113617. doi:10.1016/j.lwt.2022.113617.
18. Sayin S, Kohlhaas T, Veziroglu S, Okudan EŞ, Naz M, Schröder S, et al. Marine Algae-PLA composites as *de novo* alternative to porcine derived collagen membranes. Mater Today Chem. 2020;17:100276. doi:10.1016/j.mtchem.2020.100276.
19. Liu H, Wei L, Ba L, Yuan Q, Liu Y. Biopolymer production in microbiology by application of metabolic engineering. Polym Bull. 2022;79(8):5773–94. doi:10.1007/s00289-021-03820-9.
20. Martinez PL. Advances in biochemical engineering for biopolymer production. Am J Chem Chem Eng. 2025;6(2):11–5. doi:10.71465/ajcce1749.
21. Dong Y, Chen Z. Systems metabolic engineering of *Corynebacterium glutamicum* for efficient L-tryptophan production. Synth Syst Biotechnol. 2025;10(2):511–22. doi:10.1016/j.synbio.2025.02.002.
22. Hirasawa T, Satoh Y, Koma D. Production of aromatic amino acids and their derivatives by *Escherichia coli* and *Corynebacterium glutamicum*. World J Microbiol Biotechnol. 2025;41(2):65. doi:10.1007/s11274-025-04264-3.
23. Pittard J, Yang J. Biosynthesis of the aromatic amino acids. EcoSal Plus. 2008;3(1). doi:10.1128/ecosalplus.3.6.1.8.
24. Liu L, Bilal M, Luo H, Zhao Y, Iqbal HMN. Metabolic engineering and fermentation process strategies for L-tryptophan production by *Escherichia coli*. Processes. 2019;7(4):213. doi:10.3390/pr7040213.
25. Hectors W, Delmulle T, Soetaert WK. Metabolic engineering strategies for enhanced polyhydroxyalkanoate (PHA) production in *Cupriavidus necator*. Polymers. 2025;17(15):2104. doi:10.3390/polym17152104.
26. Ryngajłło M, Jędrzejczak-Krzepkowska M, Kubiak K, Ludwicka K, Bielecki S. Towards control of cellulose biosynthesis by *Komagataeibacter* using systems-level and strain engineering strategies: current progress and perspectives. Appl Microbiol Biotechnol. 2020;104(15):6565–85. doi:10.1007/s00253-020-10671-3.
27. Nikdel A, Braatz RD, Budman HM. A systematic approach for finding the objective function and active constraints for dynamic flux balance analysis. Bioprocess Biosyst Eng. 2018;41(5):641–55. doi:10.1007/s00449-018-1899-y.
28. Robison-Smith C, Masud N, Tarring EC, Ward BD, Cable J. A class of their own? Water-soluble polymer pollution impacting a freshwater host-pathogen system. Sci Total Environ. 2024;907(21):168086. doi:10.1016/j.scitotenv.2023.168086.
29. Sun Y, Zhang T, Lu B, Li X, Jiang L. Application of cofactors in the regulation of microbial metabolism: a state of the art review. Front Microbiol. 2023;14:1145784. doi:10.3389/fmicb.2023.1145784.
30. Moradali MF, Rehm BHA. Bacterial biopolymers: from pathogenesis to advanced materials. Nat Rev Microbiol. 2020;18(4):195–210. doi:10.1038/s41579-019-0313-3.
31. Araújo EA, de Andrade NJ, da Silva LHM, de Carvalho AF, de Sá Silva CA, Ramos AM. Control of microbial adhesion as a strategy for food and bioprocess technology. Food Bioprocess Technol. 2010;3(3):321–32. doi:10.1007/s11947-009-0290-z.
32. Busscher HJ, Weerkamp AH. Specific and non-specific interactions in bacterial adhesion to solid substrata. FEMS Microbiol Lett. 1987;46(2):165–73. doi:10.1111/j.1574-6968.1987.tb02457.x.
33. Ghosh S, Lahiri D, Nag M, Dey A, Sarkar T, Pathak SK, et al. Bacterial biopolymer: its role in pathogenesis to effective biomaterials. Polymers. 2021;13(8):1242. doi:10.3390/polym13081242.
34. Coca-Ruiz V. Biochemical programming of the fungal cell wall: a synthetic biology blueprint for advanced *Mycelium*-based materials. BioChem. 2025;5(4):33. doi:10.3390/biochem5040033.
35. Rojas-Osnaya J, Quintana-Quirino M, Espinosa-Valencia A, Bravo AL, Nájera H. Hydrophobins: multitask proteins. Front Phys. 2024;12:1393340. doi:10.3389/fphy.2024.1393340.
36. Yang Y, Zhang J, Li C. Delivery of probiotics with cellulose-based films and their food applications. Polymers. 2024;16(6):794. doi:10.3390/polym16060794.

37. Ardean C, Davidescu CM, Nemeş NS, Negrea A, Ciopec M, Duteanu N, et al. Factors influencing the antibacterial activity of chitosan and chitosan modified by functionalization. Int J Mol Sci. 2021;22(14):7449. doi:10.3390/ijms22147449.
38. Wang X, Liu M, Yu C, Li J, Zhou X. Biofilm formation: mechanistic insights and therapeutic targets. Mol Biomed. 2023;4(1):49. doi:10.1186/s43556-023-00164-w.
39. Gheorghita AA, Li YE, Kitova EN, Bui DT, Pfoh R, Low KE, et al. Structure of the AlgKX modification and secretion complex required for alginate production and biofilm attachment in *Pseudomonas aeruginosa*. Nat Commun. 2022;13(1):7631. doi:10.1038/s41467-022-35131-6.
40. Yahya EB, Jummaat F, Amirul AA, Adnan AS, Olaiya NG, Abdullah CK, et al. A review on revolutionary natural biopolymer-based aerogels for antibacterial delivery. Antibiotics. 2020;9(10):648. doi:10.3390/antibiotics9100648.
41. Wang Y. Understanding aspects of alginate biosynthesis and regulation by *Pseudomonas aeruginosa*: a thesis presented in partial fulfilment of the requirements of the degree of Doctor of Philosophy in Microbiology at Massey University, Palmerston North, New Zealand [dissertation]. Palmerston North, New Zealand: Massey University; 2017.
42. Jackson KD, Starkey M, Kremer S, Parsek MR, Wozniak DJ. Identification of *psl*, a locus encoding a potential exopolysaccharide that is essential for *Pseudomonas aeruginosa* PAO1 biofilm formation. J Bacteriol. 2004;186(14):4466–75. doi:10.1128/jb.186.14.4466-4475.2004.
43. Byrd MS, Sadovskaya I, Vinogradov E, Lu H, Sprinkle AB, Richardson SH, et al. Genetic and biochemical analyses of the *Pseudomonas aeruginosa* Psl exopolysaccharide reveal overlapping roles for polysaccharide synthesis enzymes in Psl and LPS production. Mol Microbiol. 2009;73(4):622–38. doi:10.1111/j.1365-2958.2009.06795.x.
44. Ma L, Conover M, Lu H, Parsek MR, Bayles K, Wozniak DJ. Assembly and development of the *Pseudomonas aeruginosa* biofilm matrix. PLoS Pathog. 2009;5(3):e1000354. doi:10.1371/journal.ppat.1000354.
45. Amyx-Sherer K, Reichhardt C. Challenges and opportunities in elucidating the structures of biofilm exopolysaccharides: a case study of the *Pseudomonas aeruginosa* exopolysaccharide called Pel. Magn Reson Chem. 2024;62(5):361–9. doi:10.1002/mrc.5405.
46. Coulon C, Vinogradov E, Filloux A, Sadovskaya I. Chemical analysis of cellular and extracellular carbohydrates of a biofilm-forming strain *Pseudomonas aeruginosa* PA14. PLoS One. 2010;5(12):e14220. doi:10.1371/journal.pone.0014220.
47. Franklin MJ, Nivens DE, Weadge JT, Howell PL. Biosynthesis of the *Pseudomonas aeruginosa* extracellular polysaccharides, alginate, pel, and psl. Front Microbio. 2011;2:167. doi:10.3389/fmicb.2011.00167.
48. Giuma A, Khalil HPSA, Yahya EB, Sukeksi L, Alfatah T, Nurazzi NM, et al. Green thermal insulators: a review into the role of biopolymer-based aerogels in thermal insulation applications. Polym Eng Sci. 2024;64(10):4611–29. doi:10.1002/pen.26888.
49. Bisht M, Thayallath SK, Bharadwaj P, Franklin G, Mondal D. Biomass-derived functional materials as carriers for enzymes: towards sustainable and robust biocatalysts. Green Chem. 2023;25(12):4591–624.
50. Ozuna-Valencia KH, Rodríguez-Félix F, Márquez-Ríos E, Moreno-Vásquez MJ, Graciano-Verdugo AZ, Robles-García MÁ, et al. Improving the properties of polysaccharide-based films by incorporation of polyphenols through free radical grafting: a review. Polysaccharides. 2024;5(4):672–97. doi:10.3390/polysaccharides5040043.
51. Taghi Gharibzahedi SM, Koubaa M, Barba FJ, Greiner R, George S, Roohinejad S. Recent advances in the application of microbial transglutaminase crosslinking in cheese and ice cream products: a review. Int J Biol Macromol. 2018;107:2364–74. doi:10.1016/j.ijbiomac.2017.10.115.
52. Saveleva MS, Eftekhari K, Abalymov A, Douglas TEL, Volodkin D, Parakhonskiy BV, et al. Hierarchy of hybrid materials—The place of inorganics-in-organics in it, their composition and applications. Front Chem. 2019;7:179. doi:10.3389/fchem.2019.00179.
53. Hu D, Ren Q, Li Z, Zhang L. Chitosan-based biomimetically mineralized composite materials in human hard tissue repair. Molecules. 2020;25(20):4785. doi:10.3390/molecules25204785.
54. Yahya EB. Aerogels architectures: emulating biological nano-structures from cellular foundations to organ complexity. Nano Struct Nano Objects. 2024;39:101289. doi:10.1016/j.nanoso.2024.101289.

55. Saleh WM, Yahya EB, Ahmad MI, Khalil HPSA. Exploring the properties of gelatin/chitosan bioaerogel scaffolds: toward ultra-light and highly porous materials. Polym Eng Sci. 2024;64(8):3993–4001. doi:10.1002/pen.26827.
56. Chen M, Xia L, Wu C, Wang Z, Ding L, Xie Y, et al. Microbe-material hybrids for therapeutic applications. Chem Soc Rev. 2024;53(16):8306–78. doi:10.1039/d3cs00655g.
57. Vasudevan M, Perumal V, Karuppanan S, Ovinis M, Bothi Raja P, Gopinath SCB, et al. A comprehensive review on biopolymer mediated nanomaterial composites and their applications in electrochemical sensors. Crit Rev Anal Chem. 2024;54(7):1871–94. doi:10.1080/10408347.2022.2135090.
58. Elazzazy AM, Baeshen MN, Alasmi KM, Alqurashi SI, Desouky SE, Khattab SMR. Where biology meets engineering: scaling up microbial nutraceuticals to bridge nutrition, therapeutics, and global impact. Microorganisms. 2025;13(3):566. doi:10.3390/microorganisms13030566.
59. Yadav J, Marwah H, Kumar C. Synthetic biology and metabolic engineering paving the way for sustainable next-gen biofuels: a comprehensive review. Energy Adv. 2025;4(10):1209–28. doi:10.1039/d5ya00118h.
60. Mitra R, Xu T, Xiang H, Han J. Current developments on polyhydroxyalkanoates synthesis by using halophiles as a promising cell factory. Microb Cell Fact. 2020;19(1):86. doi:10.1186/s12934-020-01342-z.
61. Koller M. Polyhydroxyalkanoate biosynthesis at the edge of water activity-haloarchaea as biopolyester factories. Bioengineering. 2019;6(2):34. doi:10.3390/bioengineering6020034.
62. Katz L, Chen YY, Gonzalez R, Peterson TC, Zhao H, Baltz RH. Synthetic biology advances and applications in the biotechnology industry: a perspective. J Ind Microbiol Biotechnol. 2018;45(7):449–61. doi:10.1007/s10295-018-2056-y.
63. Ma S, Su T, Lu X, Qi Q. Bacterial genome reduction for optimal chassis of synthetic biology: a review. Crit Rev Biotechnol. 2024;44(4):660–73. doi:10.1080/07388551.2023.2208285.
64. Zhou S, Alper HS, Zhou J, Deng Y. Intracellular biosensor-based dynamic regulation to manipulate gene expression at the spatiotemporal level. Crit Rev Biotechnol. 2023;43(4):646–63. doi:10.1080/07388551.2022.2040415.
65. Huttanus HM, Senger RS. A synthetic biosensor to detect peroxisomal acetyl-CoA concentration for compartmentalized metabolic engineering. PeerJ. 2020;8(9):e9805. doi:10.7717/peerj.9805.
66. Hoffman SM, Tang AY, Avalos JL. Optogenetics illuminates applications in microbial engineering. Annu Rev Chem Biomol Eng. 2022;13(1):373–403. doi:10.1146/annurev-chembioeng-092120-092340.
67. Nambiar K, Saravana Kumari P, Devaraj D, Sevanan M. Development of biopolymers from microbes and their environmental applications. Phys Sci Rev. 2024;9(4):1903–29. doi:10.1515/psr-2022-0219.
68. Dixon EG, Ciano L, Pordea A, Alvey K, Taresco V. Harnessing enzymes for greener polymerisations: advances in chain and step growth processes. Polym Chem. 2025;16(26):2997–3029.
69. Hayes DG. Enzyme-Catalyzed modification of oilseed materials to produce eco-friendly products. J Am Oil Chem Soc. 2004;81(12):1077–103. doi:10.1007/s11746-004-1024-2.
70. Poli A, Di Donato P, Abbamondi GR, Nicolaus B. Synthesis, production, and biotechnological applications of exopolysaccharides and polyhydroxyalkanoates by Archaea. Archaea. 2011;2011(2-3):693253–13. doi:10.1155/2011/693253.
71. Tripathi NK, Shrivastava A. Recent developments in bioprocessing of recombinant proteins: expression hosts and process development. Front Bioeng Biotechnol. 2019;7:420. doi:10.3389/fbioe.2019.00420.
72. Wang H, Li H, Lee CK, Mat Nanyan NS, Tay GS. Recent advances in the enzymatic synthesis of polyester. Polymers. 2022;14(23):5059. doi:10.3390/polym14235059.
73. Slagman S, Zuilhof H, Franssen MCR. Laccase-mediated grafting on biopolymers and synthetic polymers: a critical review. ChemBioChem. 2018;19(4):288–311. doi:10.1002/cbic.201700518.
74. Tormos CJ, Abraham C, Madihally SV. Improving the stability of chitosan-gelatin-based hydrogels for cell delivery using transglutaminase and controlled release of doxycycline. Drug Deliv Transl Res. 2015;5(6):575–84. doi:10.1007/s13346-015-0258-7.
75. Ali G, Sharma M, Salama ES, Ling Z, Li X. Applications of chitin and chitosan as natural biopolymer: potential sources, pretreatments, and degradation pathways. Biomass Convers Biorefin. 2024;14(4):4567–81. doi:10.1007/s13399-022-02684-x.

76. Prajapati AS, Panchal KJ, Pawar VA, Noronha MJ, Patel DH, Subramanian RB. Review on cellulase and xylanase engineering for biofuel production. Ind Biotechnol. 2018;14(1):38–44. doi:10.1089/ind.2017.0027.
77. Huang W. Application of synthetic biology in directed evolution to enhance enzyme catalytic efficiency. Biosci Evid. 2024;14(3):131–42. doi:10.5376/be.2024.14.0015.
78. Sui B, Wang T, Fang J, Hou Z, Shu T, Lu Z, et al. Recent advances in the biodegradation of polyethylene terephthalate with cutinase-like enzymes. Front Microbiol. 2023;14:1265139. doi:10.3389/fmicb.2023.1265139.
79. Nomura CT, Taguchi S. PHA synthase engineering toward superbiocatalysts for custom-made biopolymers. Appl Microbiol Biotechnol. 2007;73(5):969–79. doi:10.1007/s00253-006-0566-4.
80. Alias NH, Abdullah N, Othman NH, Marpani F, Zainol MM, Shayuti MSM. Sustainability challenges and future perspectives of biopolymer. In: Biopolymers: recent updates, challenges and opportunities. Cham, Switzerland: Springer International Publishing; 2022. p. 373–89. doi:10.1007/978-3-030-98392-5_17.
81. Jha K, Yahya EB, Bairwan RD, Sabri M, Abdul Khalil HPS, Ahmad MI, et al. Eco-friendly approach for carboxymethyl cellulose isolation from durian peel waste and aerogel scaffold preparation. Nano Struct Nano Objects. 2024;40:101345. doi:10.1016/j.nanoso.2024.101345.
82. Gopalakrishnan AV, Suresh H, Mariappan G, Kanagaraja A, Raman P. Industrial microbial bioprocess development: a comprehensive overview. In: Industrial microbiology and biotechnology. Singapore: Springer Nature; 2024. p. 89–154. doi:10.1007/978-981-97-6270-5_4.
83. Stelder MM, van der Schaaf J, Diender M. Downstream process intensification and techno-economic assessment of the recovery of polyhydroxyalkanoates produced in sequencing batch reactors using the membrane assisted spinning disk reactor. Eindhoven, The Netherlands: Eindhoven University of Technology; 2022.
84. Olonisakin K, Mohanty AK, Thimmanagari M, Misra M. Recent advances in biodegradable polymer blends and their biocomposites: a comprehensive review. Green Chem. 2025;27(38):11656–704. doi:10.1039/d5gc01294e.
85. Oyervides-Guajardo VG, Claudio-Rizo JA, Cabrera-Munguia DA, Cano-Salazar LF, León-Campos MI, Tamayo-Ordoñez MC. Protein-polysaccharide hydrogels: a review on smart materials for the future of biotechnology. Polym Adv Technol. 2025;36(8):e70295. doi:10.1002/pat.70295.
86. Mirsalami SM, Mirsalami M. Advances in genetically engineered microorganisms: transforming food production through precision fermentation and synthetic biology. Future Foods. 2025;11(12):100601. doi:10.1016/j.fufo.2025.100601.