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Biopolymers in Agriculture: Materials, Functions, and Pathways toward Sustainable Intensification

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Biopolymers derived from renewable biological sources or from the degradation products of living organisms are increasingly explored as functional materials in agriculture. Advances in biopolymer chemistry and processing have enabled their application across nutrient delivery, seed protection, soil conditioning, and crop protection, offering alternatives to petroleum-derived plastics and conventional agrochemical formulations. Here, we review the principal classes of biopolymers relevant to agriculture, examine their major agronomic applications, and critically assess their environmental, technical, and regulatory implications. We further highlight recent innovations and key research priorities required to translate laboratory-scale advances into robust, field-ready technologies.

Introduction

The transition toward sustainable agricultural systems demands material solutions that reduce environmental externalities while maintaining productivity. In this context, biopolymers have emerged as a promising class of materials owing to their biodegradability, biocompatibility, and compatibility with circular bioeconomy principles (Selvam *et al.*, 2025). Unlike conventional plastics and inert carriers, biopolymers can be designed to interact dynamically with soil, plants, and microbial communities, thereby enabling functional roles beyond structural support (Campanale *et al.*, 2024). Their increasing availability from agricultural residues, microbial fermentation and industrial biotechnology further strengthens their appeal as sustainable inputs for modern agriculture.

Classes of biopolymers relevant to agriculture

Biopolymers used in agricultural systems can be broadly classified into polysaccharide-, protein- and microbially derived polymers, each characterized by distinct structural features and functional potentials. Polysaccharide-based biopolymers, including starch, cellulose derivatives, chitosan and alginate, are among the most extensively studied owing to their abundance, low cost and chemical versatility (Channab *et al.*, 2023). Their hydroxyl- and carboxyl-rich backbones enable facile functionalization, crosslinking, and encapsulation, making them suitable for nutrient delivery systems and soil amendments. Protein-based biopolymers derived from plant or animal sources exhibit superior film-forming ability and barrier properties, which are particularly advantageous for seed coatings and encapsulation technologies where mechanical integrity and controlled permeability are required (Selvam & Kumar, 2024). Microbial biopolymers such as polyhydroxyalkanoates (PHAs) and polylactic acid (PLA) represent a rapidly expanding class of materials produced through fermentation-based processes. These polymers combine favourable mechanical properties with scalability, positioning them as leading candidates for biodegradable mulch films and agricultural packaging (Parida *et al.*, 2024).

Agricultural applications of biopolymers

- **Controlled-release fertilizers and nutrient carriers -** One of the most transformative applications of biopolymers in agriculture lies in controlled-release fertilizer (CRF) systems designed to synchronize nutrient availability with plant demand. Biopolymer matrices based on starch or alginate have been shown to encapsulate macronutrients and micronutrients, releasing them gradually in response to soil moisture and microbial activity (Channab et al., 2023; Chamorro et al., 2025). Such systems mitigate nutrient losses through leaching and volatilization while enhancing nutrient-use efficiency, thereby addressing both agronomic and environmental challenges associated with conventional fertilization.
- **Seed coatings and seed treatments -** Biopolymer-based seed coatings provide multifunctional platforms for seed protection, enhancement of germination and targeted delivery of bioactive compounds. Chitosan-based coatings exhibit antimicrobial activity and the capacity to elicit plant defense responses, resulting in improved seedling establishment and vigor (Selvam & Kumar, 2024). These coatings also serve as carriers for microbial inoculants, enabling localized rhizosphere colonization immediately after sowing.
- **Biodegradable mulch films -** Plastic mulch films have long been used to improve soil moisture retention and weed control, yet their persistence in soils poses significant environmental concerns. Biodegradable mulch films based on PLA, PHA and starch blends offer a viable alternative, decomposing in situ while delivering agronomic benefits comparable to polyethylene mulches (Campanale et al., 2024; Park et al., 2025). However, degradation kinetics and field performance remain strongly influenced by climate, soil microbial activity and polymer formulation (Parida et al., 2024).
- **Soil conditioners and water-retention materials -** Hydrogels synthesized from alginate and starch function as soil conditioners by enhancing water-holding capacity and buffering crops against episodic drought stress. These materials absorb and gradually release water, reducing irrigation frequency and stabilizing soil moisture regimes in arid and rainfed systems (Wang et al., 2023). Nevertheless, their long-term persistence, cost-effectiveness and interactions with soil ionic composition require careful optimization.
- **Carriers for pesticides, biocontrol agents and biologicals -** Biopolymers also enable advanced delivery systems for pesticides, pheromones and beneficial microorganisms. Encapsulation within polymeric beads or nanoparticles enhances stability, protects sensitive biologicals from ultraviolet degradation and allows targeted release at the rhizosphere or phyllosphere (Kenawy et al., 1996; Mawale et al., 2025). Such systems reduce off-target exposure and environmental contamination while improving efficacy.

Environmental, economic, and agronomic implications

The multifunctionality of biopolymers confers synergistic benefits across environmental and agronomic dimensions. Their biodegradability reduces long-term plastic accumulation and microplastic generation in soils (Campanale et al., 2024), while controlled-release systems improve input-use efficiency and reduce nutrient runoff (Channab et al., 2023). Collectively, these attributes position biopolymers as enabling tools for sustainable intensification rather than mere material substitutes (Selvam et al., 2025).

Technical and regulatory challenges

Despite encouraging progress, several constraints hinder widespread adoption. Biodegradation rates vary substantially across soils and climates, raising concerns regarding consistency and predictability (Campanale et al., 2024). In addition, processing sensitivity, mechanical property requirements and the absence of harmonized regulatory standards for soil biodegradability complicate commercialization. Addressing these challenges will require coordinated advances in material science, soil ecology and regulatory policy.

Recent advances and emerging directions

Recent innovations include stimuli-responsive biopolymers incorporating moisture-, pH- or enzyme-sensitive linkers that align nutrient or active ingredient release with plant physiological demand (Chamorro et al., 2025). Concurrently, advances in industrial biotechnology are improving the cost-efficiency and mechanical performance of PLA and PHA, narrowing the gap with conventional plastics (Parida et al., 2024).

Field evidence and case studies

Field-scale evaluations and meta-analyses indicate that biodegradable mulch films can achieve yield outcomes comparable to polyethylene mulches in vegetable cropping systems, while eliminating retrieval and disposal costs (Park et al., 2025). Nutrient-loaded alginate beads have demonstrated reduced leaching losses and enhanced nutrient uptake in pot and lysimeter studies, underscoring their potential under controlled conditions (Wang et al., 2025). However, scaling these benefits under heterogeneous field environments remains an active area of research.

Knowledge gaps and research priorities

Key research priorities include the standardization of soil biodegradability testing across agroecosystems, the development of low-cost biopolymers with improved mechanical and barrier properties, and long-term assessments of soil health impacts (Campanale et al., 2024). Interdisciplinary field trials integrating agronomy, soil microbiology and socio-economic analysis will be essential for translating proof-of-concept technologies into scalable agricultural solutions (Park et al., 2025).

Conclusion

Biopolymers offer a versatile and integrative material platform for advancing agricultural sustainability by reducing plastic pollution, enhancing nutrient-use efficiency and enabling precision delivery of agricultural inputs. Realizing their full potential will depend on aligning material innovation with soil-specific performance, regulatory clarity and value-chain optimization. With continued interdisciplinary research and responsible deployment, biopolymers could play a central role in reshaping agricultural input systems toward greater resilience and circularity.

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