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From Soil to Seed: Advancing Agriculture with Biopolymers

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Biopolymers are emerging as a sustainable solution to address the growing challenges in modern agriculture. Derived from natural sources such as plants, animals and microorganisms, these biodegradable materials offer eco-friendly alternatives to conventional synthetic inputs. This article highlights the role of biopolymers in improving soil health, enhancing seed performance and reducing dependence on chemical fertilizers and pesticides. Their application in seed coating technology promotes better germination, protects against pests and diseases and improves early plant growth. Additionally, biopolymers contribute to efficient water and nutrient management through their ability to retain moisture and enable controlled nutrient release. Despite challenges such as higher costs and limited awareness, advancements in research and technology are expanding their potential use. Overall, biopolymers provide a promising pathway toward sustainable and resilient agricultural systems, ensuring productivity while preserving environmental health.

Introduction

Agriculture is the backbone of human survival, providing food, fibre and livelihood to billions of people worldwide. However, the sector is currently facing serious challenges due to rapid population growth, climate change, shrinking natural resources and declining soil fertility. To meet the increasing food demand, farmers have relied heavily on chemical fertilizers, pesticides and intensive farming practices. While these methods have improved crop yields in the short term, they have also led to long-term environmental problems such as soil degradation, water pollution and loss of biodiversity.

In recent years, there has been a growing awareness about the need for sustainable agricultural practices that can maintain productivity without harming the environment. This has led to the exploration of eco-friendly alternatives that are both effective and safe. One such promising solution is the use of Biopolymers in agriculture. These naturally derived materials are biodegradable, renewable and capable of enhancing various aspects of crop production. Biopolymers play a significant role in improving soil structure, increasing water retention and supporting beneficial microbial activity. They also serve as carriers for nutrients and bioactive compounds, enabling their slow and controlled release. This not only improves nutrient use efficiency but also reduces losses and environmental contamination. As a result, biopolymers contribute to better soil health and sustainable crop production.

Another important area where biopolymers are making an impact is seed technology. The early stages of plant growth are critical for determining crop yield and the use of biopolymer-based seed coatings has shown great potential in improving seed germination and seedling establishment. These coatings provide physical protection to seeds, enhance moisture availability, and deliver essential nutrients and beneficial microorganisms directly to the developing plant.

Definition

Recently, concerted efforts to protect the environment not only by using natural renewable materials environmentally friendly, but also using materials that decompose naturally in the environment was done and increasing rapidly One of these materials is biopolymers, a kind of polymers, that produced by living organisms such as alginate and carrageenan which produced naturally occurring anionic polysaccharide isolated from the seaweeds (Fig. 1) , chitosan found in insects and crustaceans shells of certain other organisms, including many fungi, algae, and yeast.

Monomeric units of Biopolymers are sugars, amino acids, and nucleotides. Cellulose, starch and chitin, proteins and peptides, DNA and RNA are all examples of biopolymers. Biopolymers and their derivatives are varied, plentiful and important for life. They exhibit the characteristics of a wonderful and increasingly important for various applications. For example, these biomaterials can be divided into proteins and poly (amino acids), poly- di- and monosaccharides such as cellulose, starch, fructose and glucose.

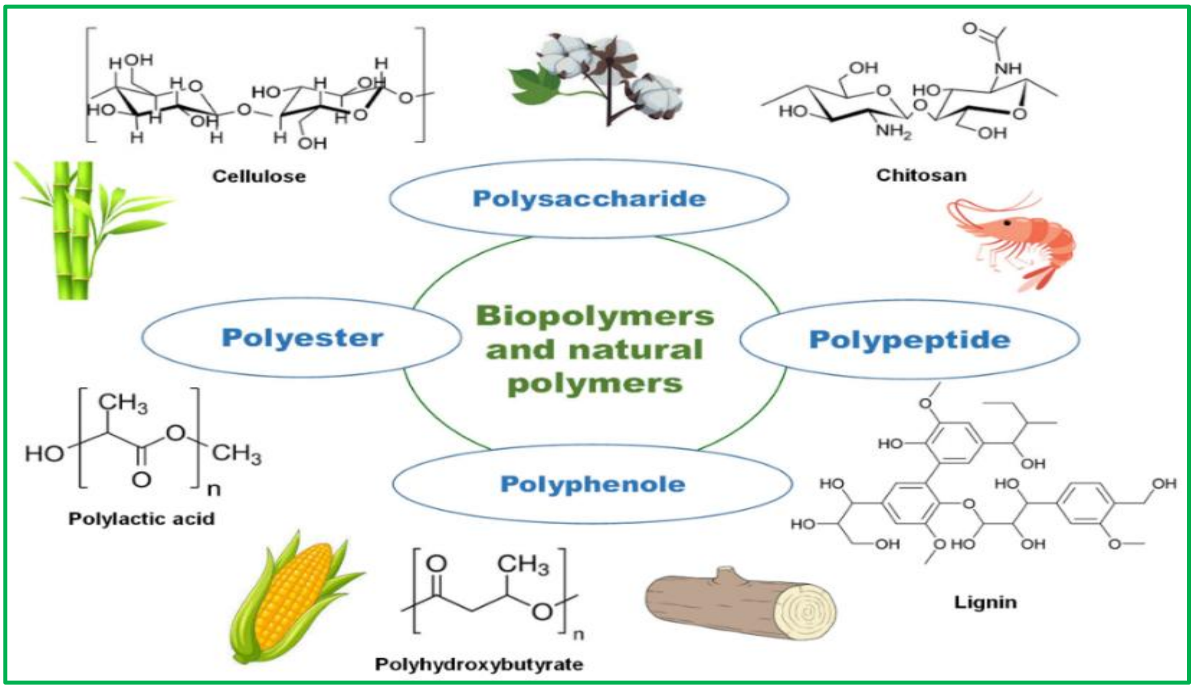

Fig 1.

Biopolymers In Agriculture

There exist two different viewpoints regarding the nature of biopolymer. A major school of thought defines biopolymer as a non-toxic, biodegradable polymer derived from the natural biomass of living organisms, i.e. plants, animals, fungi, algae, and microbial communities. While some researchers argue that every non-toxic, biodegradable and biocompatible polymer, whether it is derived from natural biomass or synthetic, may be considered a biopolymer (Baldanza *et al.* 2018; Calcagnile *et al.* 2019; Hakim *et al.* 2019; Nooeaid *et al.* 2021). The presence of many hydrophilic groups and crosslinked network structure in biopolymers enhance their water absorbency and water-retention capacity even under adverse climatic and soil conditions (Chang *et al.* 2021). Kumar Verma *et al.* (2017) stated that nano-clay polymer composites improved water-absorption and water-retention capabilities, making them effectively applicable in rainfed agriculture to mitigate water stress.

Hydrogels such as polyacrylamide have the potential to improve water use efficiency under abiotic stress conditions, and up to 95% degradation of the residual acrylamide was observed within 30 days, indicating negligible environmental persistence. Abrisham *et al.* (2018) revealed that application of acrylamide copolymer of potassium acrylate increased the soil cation exchange capacity, plant growth indices, and emergence of *Seidlitzia rosmarinus* under water deficit condition. Similarly, Seeds of *Caragana korshinskii* coated with superabsorbent polymers (SAPs) including acrylamide copolymerized with potassium acrylate and sodium acrylate showed a significant increase in emergence percentage and seed vigor, while a decrease in electrical conductivity, proline contents, and reactive oxygen species under drought stress (Qiang *et al*. 2017).

Biopolymer Seed Coating

Insecticidal and fungicidal seed treatments offer significant agricultural benefits, but they can also pose phytotoxic risks, contribute to pathogen resistance and lead to environmental contamination. Therefore, there is a growing need to replace these substances with eco-friendly natural compounds, such as biopolymers derived from plants, fungi, animals, bacteria and other microorganisms. Biopolymers have emerged as an innovative solution, enabling bioinoculant encapsulation increasing their viability and shelf life while protecting plants from biotic and abiotic factors. Seed polymer is used for coating as a thin, uniform layer over the seeds without any significant increase in seed size or weight. The major benefits of using this seed polymer are that the seed enhancement materials (fungicides, microbiological agents and micronutrients) can be directly placed on to the seed which requires smaller amount of chemicals as compared to broadcasting or surface dressing.

Seed coating is one of the most economical approaches for improving seed performance besides it has provoked the interest among many seed traders and seed companies, as it improves its marketability, brand identity and helps the farmers for easy identification of the crops and varieties based on colour. Modern seed technology provides a wide selection of enhancements that can be aimed at translating a variety's genetic potential into improved harvest and quality (Bharathi. A and Srinivasan. J., 2010).

Biopolymer-Based Seed Priming

Seed priming is a technique of controlled hydration (soaking in water) and drying that result in more rapid germination when the seeds are imbibed. (Callan *et al*., 1997). There are different methods of priming like hydropriming, halopriming, thermopriming, bio-priming etc. Biopolymer-based seed priming is an advanced seed treatment technique where natural polymers are used to enhance seed performance before sowing. It combines the concept of seed priming (controlled hydration of seeds) with biopolymers like chitosan, alginate, starch or cellulose derivatives to improve germination, vigor and stress tolerance. It includes hydro-priming with biopolymers, where seeds are soaked in polymer solutions to regulate water uptake. Film coating involves applying a thin biopolymer layer (like chitosan or alginate) on seeds for protection and uniform germination. Nano-biopolymer priming uses nanoscale polymers to improve nutrient delivery and stress tolerance.

Applications

Biopolymers function as functional matrices and carriers in agricultural systems. In controlled-release formulations, polymers such as chitosan, alginate and starch derivatives form cross-linked networks that regulate diffusion of nutrients or agrochemicals. As hydrogels, they exhibit high swelling capacity and water absorption due to hydrophilic functional groups (-OH, -COOH), thereby improving soil water potential and plant available water. Biopolymers are also used for microencapsulation and nano-encapsulation, enhancing stability, targeted delivery and reduced volatilization or leaching losses of pesticides and fertilizers. Additionally, biodegradable mulch films undergo microbial degradation via enzymatic hydrolysis, contributing to soil organic carbon without causing residue accumulation.

Biopolymer-based seed priming enhances seed performance through physiological, biochemical, and molecular mechanisms. The polymer matrix regulates imbibition rate, preventing membrane damage and enabling membrane repair and reorganization. It promotes activation of key enzymes such as α-amylase, protease, and dehydrogenase, accelerating reserve mobilization and respiration. Certain biopolymers (e.g., chitosan) act as elicitors, inducing systemic resistance via activation of defense-related pathways (PR proteins, phenolics, antioxidant enzymes like SOD, CAT, POD). Priming also improves osmotic adjustment by accumulation of compatible solutes (proline, sugars), enhancing tolerance to abiotic stresses such as drought and salinity. At the field level, this results in synchronized germination, improved seedling vigor index, better root–shoot growth and higher resource-use efficiency, ultimately contributing to yield stability.

Challenges and Way Forward

Biopolymers and biopolymer-based seed priming face challenges such as variable biodegradation, lack of standardized formulations and reduced seed shelf-life after priming. Issues in uniform coating, scalability and higher production costs further limit large-scale adoption by farmers. Environmental factors also influence performance consistency, making results less predictable across regions. Future efforts should focus on developing nano- and smart biopolymers for controlled and targeted input delivery. Improving seed storage techniques, formulation protocols and cost-effective production from local biomass is essential. Strengthening farmer awareness, extension services and policy support will accelerate adoption in sustainable agriculture.

Conclusion

Biopolymers and biopolymer-based seed priming represent a promising advancement in sustainable agriculture by integrating eco-friendly materials with improved seed performance. They enhance germination, seedling vigor and stress tolerance through well-defined physiological and biochemical mechanisms, while also supporting efficient input use. Despite challenges such as cost, standardization and storage limitations, ongoing research in nano-biopolymers, smart delivery systems and improved formulations is steadily addressing these issues. With proper technological refinement, farmer awareness, and policy support, these approaches can play a vital role in achieving resilient, resource-efficient and environmentally sustainable crop production systems.

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