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Review

Biopolymers in Seed Coating for Sustainable Agriculture

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ABSTRACT: The multibillion-dollar worldwide market for coated seeds is currently seeking new sustainable solutions that promote the use of natural (biobased) polymers for developing seed coating materials produced using clean methodologies. Seed coating is an effective method widely applied in modern agriculture. By uniformly depositing a variety of active ingredients on the seed surface, it is possible to obtain coated seeds with enhanced resistance, germination, and facilitated sowing. Moreover, seed coating is an attractive option for improving crop yield, resistance to biotic and abiotic factors, and restoring degraded soil systems. Petroleum-derived polymers are commercially used in seed coating, which can negatively affect plants, soil, and pollinating animals. Biopolymer seed coatings offer various advantages for reducing environmental contamination, enhancing seed protection, and enabling the addition of beneficial microbial species that promote plant growth. Such seed coatings also improve seed germination, nutrient delivery, and sowing efficiency, while reducing reliance on chemical inputs and contributing to environmentally responsible agriculture. This review highlights the growing importance of biopolymers in seed coating and summarizes their multifaceted use in sustainable agricultural systems.

KEYWORDS: *Seed Coating, Biopolymers, Functional Materials, Responsible Agriculture, Sustainability*

1. INTRODUCTION

Agricultural production currently faces significant and complex challenges. The core question is whether agriculture can meet the unprecedented demand for food without straining natural resources. In a scenario where the world population is growing, an expansion of agriculture can follow that trend to satisfy the increase in food demand.[1] Simultaneously, resource-intensive farming systems have inflicted significant harm on biodiversity, leading to water scarcity, soil depletion, proliferation of pathogenic emergent species, and compromising food security.[2,3] Additionally, the high levels of greenhouse gas emissions and deforestation represent a significant environmental footprint and contribute to climate change.[4]

The introduction of new technologies represents a significant shift in agriculture, promising to mitigate land abandonment and degradation, reduce agrochemical use, and promote agricultural sustainability. These innovations not only enhance productivity but also lead to substantial economic, social, and environmental benefits, aligning with the imperative to minimize the adverse impacts of agriculture on the environment.[5,6] Among the observed benefits are the emergence of new producers and the increase in areas dedicated to organic production, the growth of agricultural income, the promotion of employment, and the improvement of working conditions for the local community.[7] However, the transition from current agricultural practices to more environmentally sustainable processes is faced with a scarcity of renewable inputs, resulting in low productivity. Agricultural innovations, such as the implementation of new agrarian technologies and the introduction of improved seeds and tools, are crucial to ensure sustainability and increase production.[8,9]

The multibillion-dollar worldwide market for coated seeds[10,11] currently seeks new solutions to promote the use of natural (biobased) polymers for developing seed coating materials that are environmentally sustainable and produced by clean methodologies. The seed enhancement technologies, including seed priming and coating techniques, have improved seed performance under specific conditions. Seed coating technology has been considered a highly promising approach to relieve the pressure of agricultural activities and combat abiotic (e.g., drought and salinity) and biotic stresses (e.g., phytopathogens).[10,12] The practice of seed coating has wide applications in different crops of vegetables, ornamental plants, grasses, oilseeds, and biofuel species[10,13] and, more recently, forest species.[14]

Seed dressing constitutes a presowing technique aimed at improving seed germination, seedling establishment, vigorous growth, and overall plant survival.[15,16] It impacts crop yields by protecting seeds and seedlings from insects and diseases, ensuring uniform plant development across various soil types, agricultural practices, and environmental conditions.[17] However, the primary materials used by the seed industry are derived from petroleum sources, which negatively impact crop development and the environment.[18−20]

To address these challenges, biopolymers and copolymers derived from renewable sources or different types of waste

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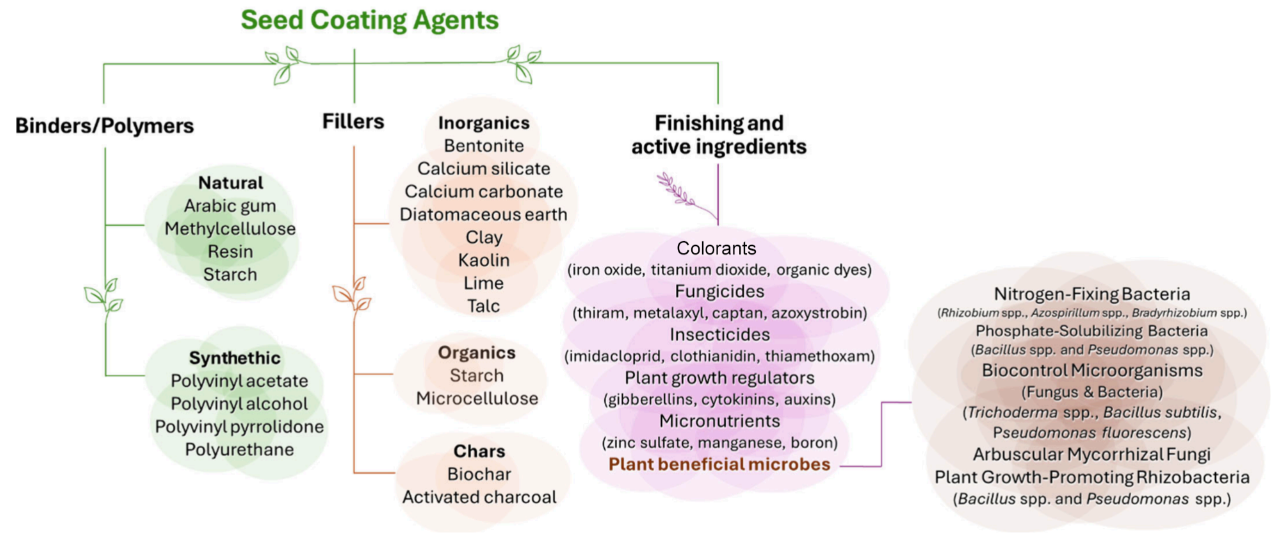

Figure 1. Schematic representation of the main components used in seed coating formulations: binders/polymers, fillers, finishing agents, and active ingredients.

have emerged as promising alternatives for seed coating.[20] These renewable materials exhibit a shorter life cycle than petroleum-based polymers and offer ecologically friendly properties.[21,22] Furthermore, the integration of beneficial microorganisms can improve seed protection and resistance to environmental stresses. However, compatibility with coating materials may be required to ensure the survival and effectiveness of the microorganisms. Considering the above discussion and the increasing demand for coated seeds, this review highlights recent studies on the use of biopolymers in seed coating and summarizes perspectives on their application in sustainable agriculture.

2. SEEDS AND SEED COATING

Seeds are one of the prominent pillars of human and animal life, known to provide the "Four F's in agriculture and land use products": Food, Feed, Fiber, and Fuels, and are essential for maintaining biodiversity and agricultural production.[23] These reproductive structures are composed of an embryo, a nutrient-providing tissue (endosperm), and a protective coat.[24−26] Seeds exhibit considerable morphological diversity with variations in size and shape (e.g., ellipsoidal, oval, cardioid, among others). Morphological variability represents natural selection for optimizing the dispersal and survival of species in different environments.[27,28] Seed preservation is crucial for sustainable farming, agricultural adaptation, and biodiversity promotion.

Seed coating technology is an ancient practice, with previous evidence dating back 2000 years from the ancient Chinese, who used mud-coated rice seeds to ensure agricultural productivity in flooded regions.[11,29] In 1868, the first patent was registered on improving the planting of cotton seeds coated with a mixture of glutinous material and gypsum.[30,31] In the 1930s, seed coating was commercially produced for the first time for cereal seeds. The extensive commercial application of seed coating began in the 1960s to increase sowing accuracy in horticulture. Since the 1980s, agrochemical companies have developed formulations based on synthetic polymers to coat seeds, and this has been so far the most widely used method in the seed coating industry.[32]

Nowadays, seed coating is an essential tool in modern and precise agriculture.[33,34] The process consists of covering seeds with balanced amounts of exogenous materials that change the physical properties of seeds and enhance their handling, quality, and performance.[5,10,13,35,36] However, negative impacts associated with seed coating have also been verified, such as delayed germination and plant emergence, the need for specific products, potential incompatibility between components of coating formulations, and the cost of the seed coating process.[2,37]

Coatings can be produced with different materials, which generally include (i) binder, (ii) filler, (iii) finishing, and active ingredients (Figure 1). Binders are liquid-applied polymers that provide adhesion, ingredient retention, and integrity.[38] Fillers usually comprise inorganic or organic fine particles that confer shape and volume, minimize physical and chemical damage to seeds, and provide a controlled release of active ingredients such as nutrients and biological control agents.[10,36,39] Some of these exogenous materials may include nutrients, plant growth regulators, and microorganisms, which can positively influence seed germination, emergence, and initial growth of seedlings.[2,10,12,22,36,39,40] As an example of a class of active ingredients, plant-beneficial microbes have been used in seed coatings to improve seed health, germination, and plant growth. Nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azospirillum*), phosphate-solubilizing bacteria (e.g., *Bacillus*, *Pseudomonas*), and mycorrhizal fungi all contribute to improved nutrient availability and uptake.[41] Additionally, biocontrol bacteria such as *Trichoderma* and *Bacillus subtilis* protect seeds from diseases, minimizing the need for chemical treatments.[42]

Since the 21st century, there has been a significant focus on seed improvement and coating.[2] With the rapid spread and development of seed coating techniques, the global market is expected to move to ~3.6 billion USD by 2027.[43] The grains and cereals segment (61% of the market) dominates in terms of the variety of seeds, for which the most investment is made in the application of coatings, followed by the vegetable sector (33%), flowers (4%), and forage (2%).[10] Seedling establishment is crucial for any crop, as seeds are exposed to various environmental pressures, namely biotic and abiotic stresses

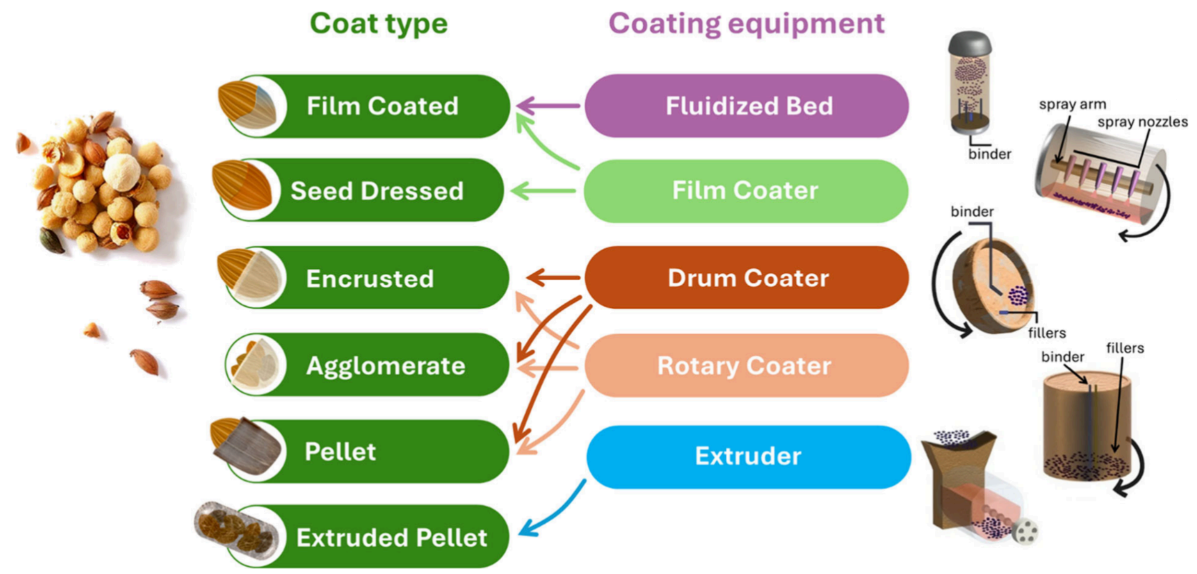

Figure 2. Representative examples of seed coating equipment for different types of seed coating techniques.

that can alter quality aspects.[44,45] Seed coating can prevent infection by pathogens during storage and germination, as well as fortify seeds to improve germination, seedling development, and overall crop productivity.[36,46]

The availability of effective coating materials and formulations compatible with biocontrol agents is essential. In addition to surface adherence, essential requirements of coating materials include adequate shelf life and the absence of adverse effects on seed germination and seedling vigor. Once planted in the soil, seed coatings must facilitate the rapid growth of any incorporated biocontrol agents.[47] The use of nonactive or active materials on the seed coating can alter the original shape and size of the seeds, thus increasing seed weight, which can facilitate handling and sowing, depending on the farming technique employed.[2,10,48]

3. SEED COATING TECHNOLOGIES

3.1. Film Coating. Seeds can be coated with a thin layer of hybrid material composed of polymers and active ingredients. The treatment involves applying a thin layer of external material, usually less 10% of the seed's weight.[2,10] Although this film does not significantly alter the shape and size of the seeds, it improves their properties and handling.[47] Compared to other types of seed coating, the main advantage of film coating is the reduced loss of active ingredients during seed handling and transportation.[42] Recently, film coating has been considered an efficient tool for improving the productivity of crops such as canola, corn, rice, soybean, and wheat.[40,47,49−51]

3.2. Seed Dressing. Seeds are coated with a thin layer of protective or beneficial substances before sowing. This methodology largely improves seed performance by protecting it from diseases, pests, and environmental stresses. Seed dressing typically involves coating seeds with fungicides, insecticides, or nutrients to improve germination, protect against pests and diseases, and enhance seed performance.[52,53] Unlike encrusting or pelleting, seed dressing applies a thin layer of treatment without significantly altering the seed size or shape. It is commonly used in agriculture to ensure healthy crop establishment and increase yields.[54] Herbicides are not frequently used as active agents in seed coatings. Unlike fungicides and insecticides, which protect seeds from diseases and pests, herbicides primarily target weeds and may cause phytotoxicity, potentially affecting seed germination.[55] Furthermore, legal limits prevent direct application of herbicides to seeds due to environmental and safety issues.

3.3. Encrusting. The encrustation process is carried out through the alternating addition of liquid and solid products, including biopolymers, in such that the weight of the seed is increased by up to 500%, with an impact on the original shape of the seed.[2,10,17] The thickness of the coating can affect the germination rate, and the encrusted seeds require more time to germinate than the film-coated ones.[56] In addition, before being packaged and stored, newly embedded seeds need to be dried until reaching their original moisture content. This approach is typically used in precision sowing and does not require thinning during postemergence.[49]

3.4. Agglomerate. Seed treatment technology designed to encapsulate several seed units from the same batch or separate batches, types, or species.[13] The process involves a significant application of adhesive ingredients, resulting in seed clumping, followed by the addition of inert elements, including soil, vermiculite, sand, and organic materials.[13,57,58] Aiming to maximize seed dispersal, boost emergence rates, and enable seedling establishment in degraded environments, this approach has been extensively embraced in forestry projects.[58]

3.5. Pelleting. The seeds are coated with liquid and/or solid materials applied to the surface of the seed, allowing for a tremendous weight increase of between 500 and 5000%.[2] Granulation changes the seed's morphology into a larger spherical shape. While seeds treated with film coating and encrusting are classified according to their weight, pellet seeds are classified according to their diameter.[10] In addition, pelleting offers the possibility of high material loading around the seeds.[17] As with the encrustation process, freshly pelleted seeds should be dried before being packaged and stored. With a larger diameter, the seeds are easily applied in precision sowing, either manually or by agricultural machinery, especially in crops that have small, low-weight, and irregularly shaped seeds that are difficult to individualize.[59]

3.6. Extruded Pellet. This process is used for encapsulating multiple seeds per pellet or one single seed per pellet.[57] It involves preparing a homogeneous matrix of inert materials,

Table 1. Examples of Biopolymers and Derivatives Utilized in Seed Coating, Highlighting the Associated Crop Cultivars, Additives, Coating Type, and Principal Advantages for Enhancing Seed Quality and Crop Productivity[a]

Biopolymers and Derivatives	Culture	Additive	Coating Type	Main Advantages of Seed Coating	Reference
Arabic Gum	Tomato	Bentonite, China powder, rhizobia, calcium oxide, and talcum	Pelleting	Better protection against environmental stress compared to uncoated seeds.	78
	Sorghum and maize	Peat substrate, fungus *Rhizophagus fasciculatus*, *Rhizophagus aggregatus*, and bacteria *Leifsonia* sp.	Film coating	Coated seeds experienced less insect damage and maintained germination capacity even after prolonged storage periods, compared to uncoated seeds.	79
Carboxymethyl Cellulose	Lettuce	CP	Pelleting	Improved precision sowing by modifying the physical characteristics of the seeds (weight and shape) and reducing the need for thinning.	80
	Soybean	CP	Film coating	Coating led to good physiological quality in seed germination and plant development.	81
Chitosan	Artichoke	WA	Film coating	Due to its antifungal activity, the chitosan-based coating improved seed germination and plant growth.	82
	Corn	Glycerol	Film coating	Coating with low concentrations of chitosan improved germination and seedling size. High concentrations of chitosan reduced the germination speed index and seedling height.	20
	Groundnut and safflower	Fungus *Trichoderma harzianum*	Film coating	The combination of biopolymers and beneficial fungi significantly increased germination and vigor and inhibited crop diseases.	83
	Soybean	Alginate and bacteria *Bradyrhizobium japonicum*	Film coating	The combination of biopolymers and bacteria led to greater emergence in the field and plant population compared to uncoated seeds.	84
Methylcellulose	Corn	Bentonite, talc, and starch	Encrusting	Owing to its antifungal activity, the chitosan-based coating improved seed germination and plant growth.	85
Pectin	Bean	Bacteria *Rhizobium tropici*	Film coating	Seed coating with rhizobacteria resulted in healthier plants and mitigated water stress.	86
	Rice	Gelatin and fungus *Trichoderma koningiopsis*	Encrusting	Seed coating enables the production of biological products.	41
Polyhydroxyalkanoates	Barley	Pullulan and bacteria *Pseudomonas flavescens*, *Bacillus aerophilus*, *Serratia proteamaculans*, and *Pseudomonas putida*	Film coating	The combination of biopolymers and beneficial microorganisms protected phytopathogens and improved seed germination and plant growth in the field.	22
Sodium Alginate	Canola	Chitosan, talc, fungus *Trichoderma harzianum*, and CP	Film coating and Encrusting	The coating enhanced root growth.	38
	Chilli and Pak-choi	Carboxymethylcellulose, gum arabic, xanthan gum and fungus *Trichoderma asperellum*	Film coating	Sodium alginate increased the survival of *Trichoderma asperellum* in seeds and their tolerance to pathogenic infection by the fungus.	87
	Sunflower	Chitosan and fungus *Trichoderma harzianum*	Pelleting	The coating improved emergence, root growth, and germination levels. Plant disease control when combined with fungi.	88
	Sweet corn	CP	Film coating	Sodium alginate, as a film on seeds, increased germination and initial growth of seedlings.	89
Soy Flour	Broccoli	Cellulose and diatomaceous earth	Encrusting	Soy flour incorporated into seed coating functions as a plant biostimulant, promoting enhanced growth and nitrogen uptake in plants.	90
Starch	Cowpea	Silicon dioxide, fungus *Rhizophagus irregularis*, and bacteria *Pseudomonas libanensis*	Encrusting	Seed coating with beneficial microorganisms improves sustainable plant cultivation in the field.	91
	Maize	Gelatin, polyvinyl alcohol, and bacteria *Azospirillum brasilense*	Film coating	The formulation of starch and gelatin is considered a promising, low-cost, biodegradable, and renewable material for use in agriculture.	77
Xanthan Gum	Finger millet	Polymer powders and sticking agent	Film coating	Recommended as a coating technique to maintain high water potential in rainfed ecosystems.	92

[a] Abbreviations used: WA - without additives; CP - commercial product.

adhesion agents, and additives into which the seeds are inserted and run via an extrusion device.[16] Under controlled pressure and temperature, the mixture is molded into specific shapes during extrusion, such as cylinders or spheres, guaranteeing uniform integration of the components involving the seeds.[60] This strategy improves sowing efficiency, particularly for species with small, irregular, or difficult-to-disperse seeds. It also promotes seedling establishment under adverse conditions, enhancing agricultural efficiency and environmental restoration.[14]

4. SEED COATING EQUIPMENT

Various types of equipment are employed for seed coating processes (Figure 2), with the most used systems including drum coaters, rotary coaters, and fluidized bed units. These technologies enable the production of pelleted, encrusted, and film-coated seeds.[2]

The drum coater, an inclined circular rotating container, was the first and most common instrument used for seed coating (e.g., pelleting).[10] The rotation of the equipment causes the seed mass to rotate in a regular flow along the drum wall, while the materials are alternately applied. Liquid materials, including biopolymer binders, administered via a spray nozzle, function as humectants, while powdered materials are introduced using a blower or applied manually.[17] The seeds are coated to the desired pellet size, sorted by size, and subjected to the drying process.[10]

Rotary coating is also widely used, allowing both encrusting and pelleting.[61] It consists of a cylindrical drum with a rotating base, the rotation of which causes the seeds to move steadily along the drum's walls. Spray nozzles release the coating mixture onto the rotating seed mass.[10,21]

The fluidized bed is a cylindrical device that suspends the seeds by the vertical/downward flow of hot air through the spray nozzle, which atomizes the coating liquid toward the seed mass.[10] The flow of hot air allows the moisture to evaporate, and this process is used for film coating.[2] Throughout the process, the equipment should ensure uniform rotation and adequate adhesion of the coating to the seeds while avoiding damage or aggregation.[17] Factors such as equipment amplitude, rotation speed, porosity, water retention capacity, and properties of coating mixtures significantly impact the coating process and quality of the final product.[56]

5. BIOPOLYMERS IN SEED COATING

The application of biopolymers in agriculture represents a desirable alternative to replace polymers derived from petroleum sources.[20,39,62] Biopolymers can be produced from natural and renewable feedstocks and are currently used in several market segments, including food packaging and agriculture applications, on account of their low ecological impact[63,64] and biodegradability.[64−67] The use of carbon-based organic materials derived from natural resources (plant biomass, fungi, algae) showed positive effects on agriculture.[2] Furthermore, some biopolymers, apart from being biocompatible, can also feature additional properties such as antibacterial and antifungal.[66,68] This opens up potential use of biopolymers as biofungicides for plants to improve their quality and agricultural efficacy.[46,69,70]

The main advantage of using biopolymers is the possibility of adjusting mechanical properties and biodegradation.[71,72] Biopolymer formulations can also be tuned for appropriate permeability, allowing for water interaction during the germination phase to initiate the growth process. Owing to the relatively short degradation rates of some suitable biopolymers when in contact with soil, biopolymer-based coatings can be metabolized by biological processes at a rate compatible with germination and plant growth processes. Some biopolymers can also act as promising materials or biostimulants,[73] and meet the critical requirements for developing seed coatings. These requirements include: (i) the absence of toxic effects on seeds when processing the coating; (ii) the promotion of adequate coating thickness and mechanical properties; (iii) the creation of a barrier effect against chemicals and water permeation; (iv) the short degradation rates; and (v) the adequate porosity to allow the transport of gases and nutrients. The most common biopolymers employed in seed coating are summarized in Table 1.

Biopolymers in seed coating protect seeds against a wide range of threats, including diseases, pests, adverse weather conditions, and high humidity. The coating layer protects seeds from damage and improves handling in sewing machines.[2] On the other hand, a necessary feature of coating films lies in their ability to avoid adverse effects on the germination process and seed vigor, while being readily dissolvable upon exposure to water.[74,75]

However, the implementation of biopolymers in seed coating encounters technical challenges and limitations that hinder its widespread adoption. The formation of a uniform and adherent coating is essential to preserve seed integrity during transport and storage, despite not easy to achieve.[20,22] The variability in surface composition among different seed species compromises biopolymer adhesion, making it difficult to obtain a homogeneous distribution of beneficial agents and other incorporated components.[22,76] Furthermore, the susceptibility of certain biopolymers to environmental factors such as abrasion, humidity, and temperature fluctuations restricts their durability and protective efficacy.[2,77]

The use of different biopolymers in seed coating showed significant beneficial effects on seed emergence rates and physiological quality, promoting greater vigor and uniformity in seedling establishment. Sene et al.[79] demonstrated that seeds coated with arabic gum could be stored for several months without loss of germination potential. The capacity of these coatings to retain and gradually release water was also demonstrated by Pathak & Ambrose,[85] who found that corn seeds coated with biodegradable hydrogel emerge more rapidly under moderate water stress conditions compared to seeds without coating. In contrast to seeds coated with synthetic polymers or uncoated seeds, Zvinavashe et al.[86] found that a biopolymer-based seed coating for common beans improves germination and drought stress tolerance in semiarid soils, as demonstrated by an increased shoot dry mass and longer roots. Biopolymer coatings also outperform uncoated seeds (85%) and synthetic polymers (90%) in terms of germination rates, reaching up to 97.4%. Additionally, biopolymers can increase the vigor of castor and peanut seedlings.[93]

In addition to improving germination, biopolymers also provide benefits in protecting seeds against pests and pathogens. Sene et al.[79] showed that arabic gum coating significantly reduced insect attacks on maize and sorghum seeds. Likewise, Usmanova et al.[22] developed biopolymer formulations containing beneficial microorganisms, such as *Trichoderma* species, which enhanced barley plant tolerance to

Fusarium pathogens. These findings highlight the potential of biopolymers not only as physical protection agents but also as carriers of bioinputs, thereby reducing the reliance on synthetic agrochemicals.

Biopolymer-based seed coatings represent a sustainable alternative to conventional chemical treatments. Chin et al.[87] and Szemruch et al.[38] emphasized that biopolymers such as sodium alginate and chitosan can enhance disease resistance and improve seedling vigor without compromising seed viability. Thus, advancements in biopolymer-based seed coatings reinforce their role as strategic tools for sustainable agriculture, combining productivity gains with reduced environmental impact.

The significant potential of novel biopolymers derived from agro-industrial residues and food processing byproducts has been highlighted by recent developments in sustainable materials science.[94] Notable sources for these biopolymers include polysaccharides extracted from fruit peels, spent coffee grounds, and other biomass residues that are high in starch. These materials are renewable, biodegradable, and strategically aligned with circular bioeconomy paradigms that promote the valorization of organic waste into high-value-added inputs.[95]

In particular, nanocellulose represents a very promising option for enhancing seed longevity and performance.[95] Nanocellulose has a number of benefits for seed coating technologies because of its physicochemical properties, especially its high specific surface area, mechanical strength, and remarkable capacity to form homogeneous and ultrathin films.[95,96] These benefits include better adhesion of active compounds and control over their release behavior, as well as improved seed protection.[97] The agronomic use of nanocellulose is still in its infancy despite potential technological advantages. Consequently, further research is essential to comprehensively elucidate the formulation stability in complex matrices, the biocompatibility with beneficial microbial consortia (e.g., inoculants and biostimulants), and the overall technical and economic feasibility of large-scale commercial implementation of nanocellulose-containing coated seeds.[96]

The commercialization of seeds coated with biopolymers faces diverse regulatory challenges worldwide. For example, strict environmental regulations and demanding standards for material biodegradability and certification in the European Union make approval procedures time-consuming, which restricts the introduction of new products into the market.[11] In the United States, despite a more streamlined regulatory pathway for biobased inputs provided by the Environmental Protection Agency (EPA), the lack of particular regulations for biopolymers is a major obstacle.[98] In Latin American countries, such as Brazil, there is currently no specific legislation governing the use of biopolymers for seed coating. The registration and implementation of biodegradable coatings may be limited by the absence of specific guidelines, even though general rules regarding seed treatment and bioinputs apply. A major obstacle in certain regions of Africa is the absence of technical infrastructure for regulatory validation and compliance testing.[99]

The commercial adoption of biodegradable seed coatings is confronted with a variety of regionally specific obstacles. Small-scale producers in Europe have limited access to seed coating technologies and products due to strict regulatory requirements and high certification costs, which primarily limit the use of coated seed to large companies. A higher price of biopolymers in comparison to synthetic analogues is still a significant obstacle to widespread use in the US. In Asian countries such as India and China, despite substantial industrial capacity for large-scale production, challenges persist in ensuring product quality standardization and material traceability. Conversely, in regions of Africa and Latin America, technological dependence on external suppliers and elevated importation costs hinders the development of local value chains for biopolymer-coated seeds.[100]

Table 2 presents a comparative analysis of the biopolymers and synthetic polymers employed in seed coating. This analysis may provide a basis for assessing the technical and economic viability of each approach, highlighting main characteristics and limitations, and considering both agronomic performance and long-term sustainability.

Further research on the use of biopolymers in seed coating is needed to make it a feasible and generally accepted agricultural practice with several promising advantages. Given the inherent variety of biopolymer properties, one of the most significant issues is the complexity of the formulations.[11] To maximize coating performance, it may be necessary to employ multi-component mixtures of various biopolymers. Additionally, the limited research on the long-term effects of these materials represents a constraint, despite their well-documented short-term benefits. The sustainability of biopolymer use in seed coating across different agricultural systems remains insufficiently understood.[102] To ensure the feasibility of this technology, the development of public policies and regulatory frameworks that guarantee both the efficacy and safety of biopolymer-coated seeds is essential, thereby fostering a sustainable transition within the agricultural sector.[11,103]

6. SYNERGY OF BIOPOLYMERS AND BENEFICIAL MICROORGANISMS

The use of beneficial microorganisms (e.g., biocontrol agents, plant-growth promoters, and biofertilizers) in coated seeds is an attractive and simple method with potential application in a wide variety of plant species.[91] It can also minimize the negative environmental impacts associated with the use of agrochemicals.[79,103,104] The most common examples of beneficial microorganisms comprise: (i) bacteria that promote plant growth, such as rhizobia (associated with legumes), and (ii) beneficial mycorrhizal fungi. Applied together with coating materials, such bioagents are essential for microbiome survival and longevity.[105] The precise application of small amounts of bioagents and their adhesion to the seed's surface or inclusion into seed coating formulation ensures that the microbial population is readily accessible during germination, at early stages of plant development, and consequently in the soil (Figure 3).[91,106]

Biopolymers are typically used in association with bacteria from the genera *Azospirillum*, *Bacillus*, *Bradyrhizobium*, *Leifsonia*, *Pseudomonas*, *Rhizobium*, and *Serratia* in crops such as barley, beans, maize, soybean, sorghum, and tomato.[22,34,77,79,84,86,91] Fungi from the genera *Aureobasidium*, *Rhizophagus*, and *Trichoderma* are used in crops such as cabbage, canola, cowpea, groundnut, maize, pepper, rice, safflower, sorghum, and sunflower.[5,38,41,79,83,87,88,91]

Microbial inoculant seed coatings can alleviate biotic and abiotic stresses and enhance crop growth.[76,91,104] Microorganisms coated on seeds protect the seedlings from various diseases, provide small amounts of inoculum to the rhizosphere, promote colonization during germination and early development stages, and increase productivity.[12,107] Furthermore, microbial seed coating is considered a cost-effective technique for the large-scale application of microbial inoculants.[76,84] However, the compatibility of biopolymers with beneficial microorganisms is also crucial, as some materials may compromise the viability of these organisms during storage, thereby reducing their efficacy in the field.[22,77]

Additional research in this direction is necessary to assess the long-term feasibility of biopolymer-based seed coatings, also considering the persistence of beneficial microorganisms and their effects on crop agronomic performance.[5,38,79] Some studies demonstrated that viable propagules of *Trichoderma harzianum* and *Bradyrhizobium* can remain active in the soil for extended periods, playing a crucial role in promoting plant growth and agricultural sustainability.[103] Microbial-containing seed coatings can promote sustainable and responsible agriculture by improving soil health, drought and stress tolerance, and environmentally friendly farming practices. Such biocoatings are a key innovation in modern sustainable agriculture, with benefits varying from better nutrient efficiency and reduced disease pressure to improved resistance. Moreover, investigations into the compatibility between different biopolymers and microbial strains are essential to understand how these coatings influence microbial viability and functionality, both during storage and after application, considering that certain materials may compromise microbial survival and reduce their effectiveness in the field.[22,105,107] Additionally, the evaluation of the impacts of environmental stress factors, such as drought, salinity, and pest pressure, on the performance of biopolymer coatings is critical for enhancing their stability and resilience under diverse agricultural conditions, which can contribute to the large-scale adoption of this technology.[34,103]

7. SYNTHETIC POLYMERS VS. BIOPOLYMERS IN SEED COATINGS

Different synthetic polymers have also been used for seed coating (Table 3). Seed coatings based on polymers from nonrenewable sources may cause environmental concerns due to their nonbiodegradability and increased production and accumulation of microplastics.[108] In contrast, uncoated seeds are susceptible to pathogen action and weather interference. This forces farmers to use chemicals in the early stages of crop development, increasing production costs and leading to adverse environmental impacts (Figure 4).[37]

Synthetic seed coating fragments are classified as microplastic coating film fragments (MPCF), characterized by dimensions of less than 5 mm, typically less than 1 mm for microplastics.[18,19,61] With direct deposition during planting, once in the soil, these coating fragments can trigger various processes, such as inhibition of germination, reduction in plant height, and toxicity, as well as changes in the chemical, physical, and biological properties of the soil matrix. These adverse effects are visible in the macrofauna[109] and the soil seed bank,[37] and persist in the soil.[110] In addition, some adverse effects of chemically coated seed dust can be observed on nontarget organisms (e.g., mortality of bee colonies, other pollinators, and terrestrial birds), causing a decline in the diversity and distribution of pollinators in the agricultural landscape. The dust is released by abrasion during the handling and planting operations of coated seeds (Figure 4).[18,111] Furthermore, the accumulation of microplastics and hazardous chemicals in plant tissues can adversely impact human health.[112]

Table 2. Properties and Comparative Performance of Seed Coatings Based on Biopolymers and Synthetic Polymers

Parameters	Biopolymer Seed Coatings	Synthetic Polymer Seed Coatings	Reference
Biodegradability	**High:** Derived from natural sources, coatings are biodegradable, decompose in the soil and show minimum environmental persistence.	**Low/Negligible:** Generally nonbiodegradable, these materials persist in the environment for extended periods, contributing to microplastic pollution.	11
Lifecycle Cost	**Potentially lower in the long term:** While initial costs might be comparable or slightly higher, the absence of microplastic residues can reduce future environmental management investments.	**Potentially higher in the long term:** Environmental persistence can incur indirect costs related to soil and plant contamination.	101
Compatibility	**Excellent:** Demonstrates high compatibility with seeds and surrounding environments, facilitating controlled release of active ingredients and providing effective protection. Biopolymer coating are typically nontoxic and biodegradable.	**Good:** Offers effective protection and adhesion to the seed, with controlled release of agrochemicals. However, concerns may arise regarding the leaching of toxic substances or microplastics into the environment.	10
Agronomic Performance	**Promising and evolving:** Capable of enhancing seed germination, promoting early seedling vigor, and providing protection against pathogens and pests. Biopolymer seed coatings can serve as carriers for beneficial biological agents (e.g., microorganisms, nutrients).	**Well-established and widely utilized:** Proven efficacy in seed protection, optimization of planting precision, and controlled release of synthetic chemicals.	2
Financial Cost	**Variable, but increasingly competitive:** The cost is still relatively high, partly due to the limited production scale. However, recent advances in production technologies (use of waste materials and microorganisms) gradually enhance financial feasibility.	**Generally low:** Petroleum-derived polymers are produced on a large scale using well-established technologies and widely adopted industrial processes.	17
Practical Limitations	**Potentially reduced durability in some cases:** May exhibit slightly lower shelf life or mechanical strength compared to certain synthetic polymers. Requires more specific storage conditions.	**Environmental impact:** The primary limitation is their significant environmental footprint, characterized by the persistence of microplastics and chemical residues.	11

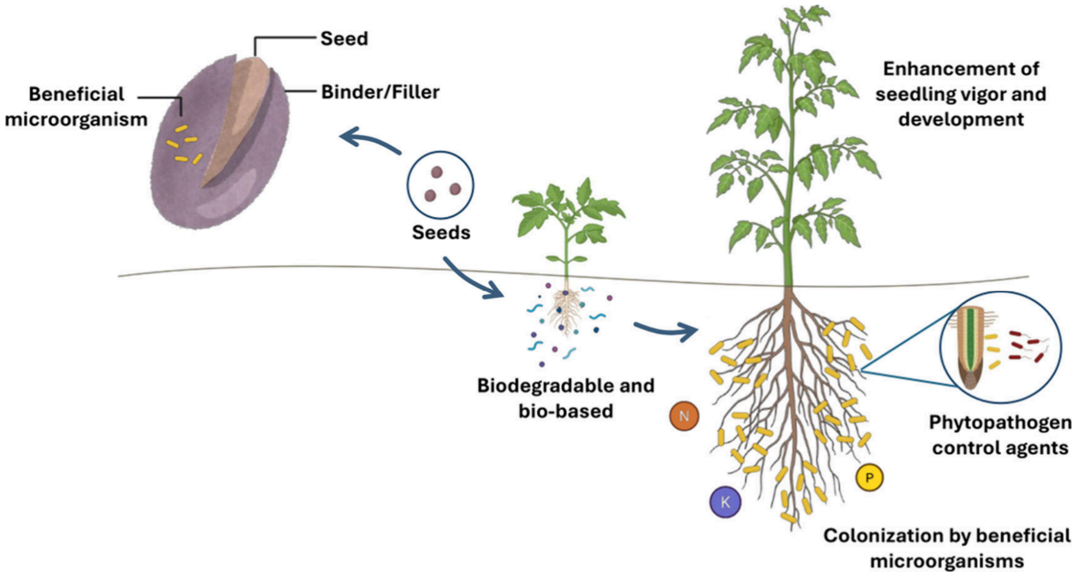

Figure 3. Sequential process for enhancing agricultural seeds via biopolymer-mediated microbial coating. Schematic representation details the application of biopolymers and beneficial microorganisms to agricultural seeds, and includes the following main steps: a) seeds are encapsulated with a biopolymer matrix containing beneficial microorganisms; b) during initial plant development, the microbial population becomes readily available in the rhizosphere; and c) the resulting root-associated microbiota promotes nutrient acquisition and confers protection against soilborne pathogens.

Table 3. Representative Synthetic Polymers Utilized in Seed Coating Across Diverse Crops

Synthetic Polymer	Abbreviation	Culture	Reference
Phosphazene	PPZ	Cowpea	113
Polylactic acid	PLA	Wheat	114
Polyvinyl acetate	PVAc	Colza, corn, rice, sorghum, soybean, cocona, stylosanthes	40, 59, 115−119
Polyvinyl alcohol	PVOH, PVA, or PVAL	Black gram, canola, cotton, groundnut, maize, soybean	77, 120−123
Polyvinylpyrrolidone	PVP	Cowpea	113, 124

The main challenge in replacing synthetic polymers used in seed coating formulations is to maintain agricultural efficacy. Synthetic polymers can show the advantage of being easily tailored to desired properties through the incorporation of copolymers or functionalized monomers, making their substitution more challenging. In this regard, the use of biodegradable biopolymers derived from biomass, organic waste, and renewable resources may offer additional benefits, such as increased water absorption capacity, which can promote favorable effects on seed germination, plant growth, and resistance to stress in stressful environmental conditions. Furthermore, these polymers can act as nutrient sources,

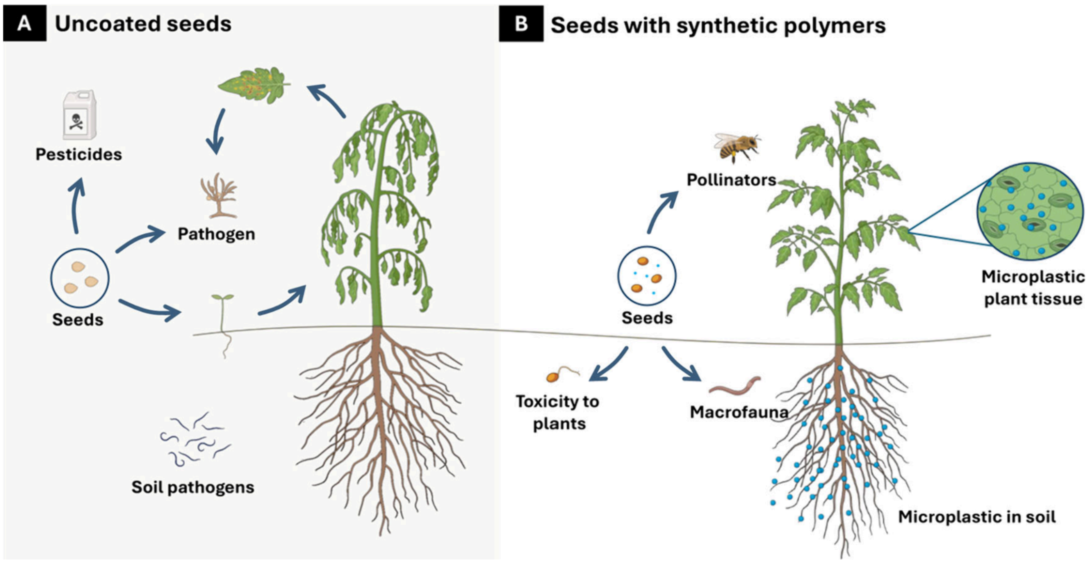

Figure 4. Schematic comparative representation of the distinct outcomes when using uncoated seeds vs. seeds treated with synthetic polymer coatings. A) Uncoated seeds are susceptible to early stage or developmental pathogen attacks, thus requiring the use of chemicals during seedling establishment. B) The use of synthetic polymers introduces negative impacts, such as harm pollinators during planting, inhibit or exhibit toxicity to seeds, and release microplastics into the soil with detectable presence on leaf surfaces.

enhancing soil fertility as they degrade, thus providing a more sustainable solution compared to synthetic polymers.[11,106]

8. PERSPECTIVES ON THE USE OF BIOPOLYMERS IN SEED COATING

The growing demand for sustainable agricultural solutions prompted research for the use of biopolymers in seed coating, revealing their capacity to improve germination, promote uniform seedling emergence, and minimize reliance on synthetic inputs. The reviewed literature indicates that biopolymers provide a viable and environmentally friendly alternative to seed coating solutions based on synthetic polymers, with the ability to incorporate beneficial microorganisms and increase crop resistance to environmental stress. Furthermore, formulations based on biopolymers support the objectives of environmentally conscious and responsible agriculture by providing inherent biodegradability and reducing contamination by microplastic.

However, challenges such as formulation stability under different environmental conditions, compatibility with distinct plant species, and production costs must be overcome before this technique can be widely implemented. Given that the interactions between biopolymers and beneficial bacteria are complex, further studies are needed to ensure that beneficial characteristics remain over time, from seed storage to the early stages of plant growth.

Further research should focus on developing innovative and scalable formulation strategies that improve the practical functionality, ecological sustainability, and cost-effectiveness of biopolymer-based seed coatings. A promising strategy to improve coating uniformity, allow the controlled release of nutrients and biostimulants, and customize bioactive functionalities to particular agronomic requirements is the integration of cutting-edge technologies like nanotechnology, bioengineering, and advanced materials. Besides, to confirm the sustainability and safety of biopolymers, a thorough assessment of their ecotoxicological profiles and environmental fates is necessary. The establishment of supportive legislation and regulatory frameworks that promote the use of ecologically friendly inputs will also be necessary for the broad adoption of such technologies. The transition to more sustainable and regenerative agricultural systems will therefore demand the coordinated political, economic, and institutional efforts in addition to scientific and technological advancements.

Biopolymers have significant potential to revolutionize the agricultural sector by contributing to environmental preservation and promoting sustainability in food production. Further research may result in the application of biopolymers (including those extracted from agricultural waste) as a viable alternative to seed coating in sustainable farming operations. Biopolymers are expected to play a critical role in the future of agriculture, and their continued development may contribute to building more resilient and responsible agricultural production systems.

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Notes

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