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Precision Seed Coating: Integrating Polymers, Bioactive Materials and Smart Technologies

*Arpita Priyadarsini, Soubhagya Behera and Masoom Ankit Patel
Department of Seed Science and Technology, College of Agriculture, OUAT, Bhubaneswar, Odisha, India- 751003
*Corresponding Author's email: arpitapriyadarsini2019@gmail.com

Precision seed coating has emerged as a significant technological innovation aimed at improving seed performance and crop establishment during the early stages of plant growth. Agriculture today faces multiple challenges such as climate variability, declining soil fertility, limited water availability, and increasing pest and disease pressure. Addressing these issues requires efficient technologies that enhance seed resilience and productivity. Precision seed coating involves covering seeds with a thin layer of functional materials including polymers, micronutrients, bioactive substances, and beneficial microorganisms. Polymers serve as binding agents that attach coating components to the seed surface and regulate the release of nutrients and other active compounds. Superabsorbent polymers improve water retention around the seed, which is particularly useful in drought-prone environments. The incorporation of micronutrients like zinc and iron enhances early plant growth and metabolic processes. Additionally, plant beneficial microorganisms included in coatings contribute to improved nutrient availability and protection against soil-borne pathogens. Recent developments in nanotechnology and smart coating systems have further enhanced the efficiency of seed coatings by enabling controlled and responsive nutrient release. These technologies support better germination, improved seedling vigour, and efficient input utilization. Overall, precision seed coating contributes to higher crop productivity while reducing excessive dependence on fertilizers and chemical treatments, thereby promoting sustainable agricultural practices (Javed *et al.*, 2022; Sharma *et al.*, 2015).

Keywords: Precision seed coating, polymers, bioactive materials, superabsorbent polymers, plant beneficial microorganisms, nanotechnology, sustainable agriculture.

Introduction

Global agriculture is increasingly challenged by environmental stress factors such as irregular rainfall, soil degradation, nutrient deficiencies, and rising temperatures. At the same time, the demand for food continues to increase due to rapid population growth. These pressures require innovative agricultural technologies that can improve crop productivity while maintaining ecological balance. One such promising innovation is precision seed coating, which enhances seed performance by delivering essential inputs directly to the seed surface.

The seed represents the initial stage of the crop life cycle, and successful germination is crucial for establishing a healthy plant population. However, seeds planted in field conditions often face several stresses including drought, salinity, nutrient limitations, and pathogen attacks. Precision seed coating provides a protective and supportive microenvironment around the seed by incorporating nutrients, protective agents, and biological materials into the coating layer. Unlike traditional seed treatments that mainly focus on protecting seeds from pests and diseases, precision seed coating is a multifunctional technology. It integrates advances from polymer science, microbiology, nanotechnology, and agricultural engineering to enhance germination and early seedling development. By delivering nutrients and beneficial microorganisms directly to the seed, this technology improves resource use efficiency and reduces environmental impacts associated with excessive chemical inputs (Taylor & Salanenka, 2012; Javed *et al.*, 2022).

Development of Seed Coating Technology

The practice of treating seeds is not new. Historically, farmers used natural materials such as ash, plant extracts, and clay to protect seeds against pests and diseases. With the advancement of agricultural science during the nineteenth and twentieth centuries, chemical fungicides and insecticides were introduced for seed protection. These early techniques typically involved dusting or slurry applications that provided limited control and lacked uniform distribution. Advancements in coating equipment later enabled the development of more precise seed treatment methods. Technologies such as rotary coaters, pan coaters, and fluidized bed systems made it possible to apply coating materials in thin and uniform layers without damaging the seed. As the technology evolved, the purpose of seed coating expanded beyond simple protection to include nutritional supplementation and biological enhancement. Modern seed coating technologies can be classified into different categories depending on the extent of coating applied. Film coating involves applying a very thin layer that does not significantly alter the size of the seed. Encrusting adds more material, increasing the weight while retaining the seed's shape. Pelleting, on the other hand, greatly modifies the seed size and shape, making it suitable for precision sowing in small-seeded crops. These innovations have transformed seed coating from a simple protective method into a sophisticated tool for improving crop establishment and productivity (Sharma *et al.*, 2015).

Importance of Polymers in Seed Coating

Polymers are fundamental components of precision seed coatings. They function primarily as binding agents that attach coating materials to the seed surface and form protective films. The properties of the polymer determine the durability, permeability, and overall performance of the coating. Synthetic polymers such as polyvinyl alcohol, polyvinyl acetate, methyl cellulose, and carboxymethyl cellulose are widely used in seed coating formulations. These polymers possess strong adhesive characteristics and provide stable coating structures. However, increasing environmental concerns about synthetic materials and microplastic accumulation have led to growing interest in biodegradable alternatives.Bio-based polymers derived from natural sources such as starch, cellulose, chitosan, alginate, and natural gums are gaining popularity. These materials degrade naturally in soil, reducing environmental pollution. Chitosan, for instance, not only functions as a binder but also exhibits antimicrobial properties that help protect seeds against pathogens. In addition, polymer coatings regulate the release of nutrients and active ingredients, ensuring gradual availability and minimizing nutrient losses due to leaching (Accinelli *et al.*, 2018; Patra *et al.*, 2022).

Superabsorbent Polymers and Moisture Management

Water availability plays a critical role in seed germination. In many regions, irregular rainfall and drought conditions hinder successful crop establishment. Superabsorbent polymers (SAPs) are widely used in seed coatings to address this challenge. SAPs are hydrophilic polymer networks capable of absorbing large amounts of water relative to their own weight. When incorporated into seed coatings, they act as miniature water reservoirs around the seed. These polymers absorb soil moisture during wet conditions and gradually release it when the surrounding environment becomes dry. As a result, the seed remains hydrated for a longer period, promoting germination and early seedling growth. Both synthetic and bio-based SAPs are used in agriculture. Synthetic polymers such as polyacrylamide possess high water retention capacity but may persist in soil. Alternatively, biodegradable SAPs developed from starch-based polymers offer environmentally friendly solutions. Research continues to focus on improving the water retention capacity of these materials while maintaining ecological safety (Su *et al.*, 2017; Menceloğlu *et al.*, 2022).

Bioactive Materials and Nutrient Supply

Precision seed coatings frequently include macro- and micronutrients that support early plant development. Delivering nutrients directly to the seed ensures that emerging roots have immediate access to essential elements. Micronutrients such as zinc, iron, manganese, and boron play important roles in enzymatic reactions, hormone regulation, and cell division. Deficiencies of these elements during early growth can significantly limit crop productivity. Incorporating micronutrients into seed coatings synchronizes nutrient availability with the germination process, thereby improving nutrient use efficiency. In addition to nutrients, seed coatings may contain plant growth regulators and biostimulants. These substances enhance root growth, stimulate metabolic activity, and improve plant tolerance to environmental stresses. Because the application is localized at the seed surface, smaller quantities of inputs are required compared to traditional soil fertilization methods, contributing to sustainable input management (Javed *et al.*, 2022).

Incorporation of Plant Beneficial Microorganisms

Plant beneficial microorganisms (PBMs) have gained considerable attention in sustainable agriculture due to their ability to enhance plant growth and soil health. Common examples include nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and beneficial fungi such as Trichoderma and arbuscular mycorrhizae. When applied through seed coatings, these microorganisms establish early associations with plant roots. Nitrogen-fixing bacteria help convert atmospheric nitrogen into forms that plants can utilize, while phosphate-solubilizing bacteria transform insoluble phosphorus compounds into accessible forms. Fungi like **Trichoderma** not only suppress soil-borne pathogens but also stimulate root development through the production of bioactive metabolites. One of the main challenges associated with microbial seed coatings is maintaining microbial viability during storage. Protective carriers such as peat, biochar, and polymer encapsulation systems are often used to ensure the survival of microbial cells until sowing. Proper formulation and moisture management are essential to maintain the effectiveness of microbial inoculants (Backer *et al.*, 2018; Kavusi *et al.*, 2023).

Smart Technologies and Nanotechnology in Seed Coatings

Recent advancements in nanotechnology have significantly expanded the potential of seed coating technologies. Nanomaterials possess extremely small particle sizes and large surface areas, which improve the efficiency of nutrient delivery and uptake by plants. Nanocarriers can encapsulate active compounds and release them slowly over time. This controlled release mechanism reduces nutrient losses and ensures sustained availability during early plant development. In addition, smart polymer coatings can respond to environmental conditions such as moisture and temperature. For example, moisture-responsive coatings swell in the presence of rainfall and release nutrients when soil moisture is adequate. Temperature-sensitive coatings may regulate permeability to protect seeds from extreme temperature fluctuations. Such smart systems transform seed coatings from passive protective layers into active regulators of the seed microenvironment. Future integration with digital agriculture tools and sensor-based technologies may further optimize seed coating formulations tailored to specific climatic and soil conditions (Patra *et al.*, 2022).

Environmental and Economic Implications

Precision seed coating contributes to environmentally sustainable farming by reducing the overall quantity of agrochemicals applied to fields. Since nutrients and protective compounds are delivered directly to the seed, losses through leaching and runoff are minimized. This reduces contamination of water bodies and protects non-target organisms. Improved germination and uniform crop establishment also enhance resource use efficiency, leading to better yield stability. However, the cost of advanced coating technologies may limit their adoption among smallholder farmers. Developing affordable biodegradable materials and cost-effective manufacturing techniques is essential to ensure wider accessibility.

Furthermore, the use of nanomaterials and synthetic polymers requires appropriate regulatory oversight to ensure environmental safety. Long-term studies on soil health and ecological impacts will be necessary to guide responsible use of these technologies.

Conclusion

Precision seed coating represents a major advancement in modern agricultural technology. By integrating polymers, nutrients, beneficial microorganisms, and smart materials, this approach enhances seed germination, improves nutrient availability, and strengthens plant tolerance to environmental stresses. The technology also promotes sustainable agriculture by reducing dependence on chemical fertilizers and pesticides. As climate change continues to threaten global food production, innovations at the seed level will play a crucial role in ensuring resilient cropping systems. Continued research focusing on biodegradable materials, smart responsive coatings, and region-specific formulations will further improve the efficiency and sustainability of precision seed coating technologies.

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