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Harnessing the Potential of Chitosan for Improving Seed Quality and Agricultural Performance

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Chitosan, a biodegradable and biocompatible polymer derived from chitin, has emerged as a potential, environmentally acceptable seed treatment agent in modern agriculture. Its multipurpose features, such as antibacterial activity, stimulation of plant defence mechanisms, and increase of antioxidant systems, all help to improve seed germination, vigour, and early seedling development. Chitosan treatments have been demonstrated to boost resistance to seed-borne infections, increase phenolic compound buildup, and improve tolerance to abiotic conditions like drought and salinity. Seed priming, coating, and nano-priming are some of the application strategies that enhance its practical utility. Despite known advantages across a variety of crops, constraints such as species-specific responses, formulation heterogeneity, economic feasibility, scalability, and limited field validation prevent widespread implementation. Overall, chitosan-based seed treatments are a sustainable and creative approach to seed science and technology, with great potential for incorporation into environmentally friendly agricultural production systems.

Keywords: Chitosan, Seed treatment, Seed germination, Stress tolerance, Seed coating, Sustainable agriculture

Introduction

Seed quality and early plant establishment are important factors influencing agricultural productivity. Seed treatments aim to boost germination, protect against both abiotic and biotic stress and increase seedling vigour (Cardarelli *et al.*, 2022). With increased concerns about environmental safety, pesticide resistance, and the harmful effects of chemical seed treatments on soil health, there is a greater need for eco-friendly and biologically based seed enhancement techniques. Natural polymers, such as chitosan, a biodegradable and biocompatible polysaccharide produced from chitin, have emerged in recent decades as viable seed treatment agents due to their multifunctional biological activity. Chitosan's unique features, such as antibacterial activity, biodegradability and ability to control plant defensive responses, make it a viable alternative to synthetic chemicals in seed technology (Shcherban, 2023).

Chitosan, in addition to protecting against seed-borne and soil-borne diseases, promotes plant growth by activating physiological and biochemical processes during germination and early seedling development (Lyalina *et al.*, 2023). Furthermore, it stimulates plant defence mechanisms by activating signalling pathways linked to Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR) (Chowdhury *et al.*, 2025). It boosts antioxidant enzyme activity, maintains phytohormone balance, and promotes membrane stability in the midst of stresses like drought, salinity, and extreme temperatures. These combined effects not only increase germination percentage and uniformity, but also help seedling establishment in unfavourable field circumstances (Lyalina *et al.*, 2023).

Therefore, the use of chitosan as a seed treatment represents a novel and sustainable approach to modern seed science and technology, combining plant physiology, molecular biology, and environmentally responsible crop management approaches.

What is Chitosan?

Chitosan is a linear polysaccharide derived from the deacetylation of chitin, which is present in crustacean shells (e.g., shrimp, crab) and fungal cell walls. It consists of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units. It is one of the most studied bioactive chemicals in agriculture due to its eco-friendliness, which includes being non-toxic, biodegradable, and renewable (Lyalina *et al.*, 2023).

Mechanisms of Action in Seed Treatment

Chitosan improves seed performance through multiple biological pathways:

1. Protection Against Pathogens

Chitosan has natural antibacterial action. It can directly suppress fungal pathogens by interfering with cell membranes and depriving bacteria of vital nutrients, hence lowering infection rates on treated seeds. Chitosan treatments were shown in fenugreek and other crops to considerably reduce fungal growth and disease severity caused by *Fusarium solani*. Treated seeds exhibited increased defence enzyme activity (e.g., chitinase, β-1,3-glucanase), suggesting an induced defence response (Ghule *et al.*, 2021).

2. Induced Resistance and Phenolic Accumulation

Chitosan can activate plant defence mechanisms, resulting in increased synthesis of phenolic chemicals and lignin precursors. Wheat seeds treated with chitosan had higher levels of antibacterial phenolic acids and lignin, which help prevent disease transmission during seed germination. Enhanced metabolite accumulation contributes to induced resistance in seedlings (Deshaies *et al.*, 2022).

3. Enhancement of Antioxidant Defence

Chitosan seed priming has been demonstrated to activate antioxidant systems including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). These enzymes reduce oxidative damage in germinating seeds under stress (e.g., water deficiency), improving germination and seedling development. Such mechanisms were demonstrated in white clover during drought circumstances (Ling *et al.*, 2022).

Effects of Chitosan on Seed Germination, Seedling Growth, and Stress Tolerance

1. Germination Percentage and Speed of Seedling Growth

Chitosan treatments have consistently improved seed germination metrics. In studies on sesame and bean seeds, chitosan coatings boosted germination percentages and accelerated germination speed index when compared to untreated controls. Enhanced root and shoot development were also reported, indicating better early seedling vigour (Godínez-Garrido *et al.*, 2022).

2. Response Under Stress Conditions

Drought and salinity are substantial constraints in agriculture. Chitosan priming has been shown to be particularly effective under water stress, boosting dehydration-responsive pathways while preserving membrane integrity. Under water deficit, seeds treated with chitosan displayed higher expression of dehydration-responsive genes and enhanced antioxidant activity, resulting in improved germination relative to untreated seeds (Ling *et al.*, 2022).

3. Fungal Disease Management

In addition to preventing pathogens, chitosan may decrease disease transmission from seed to seedling. For instance, in wheat seeds infected with *Fusarium graminearum*, chitosan treatments reduced pathogen incidence, controlled disease spread, and enhanced seed quality metrics such as germination and vigour (Deshaies *et al.*, 2022).

4. Synergistic Coatings

Modern seed coatings use chitosan as a biopolymer matrix to efficiently transport beneficial microorganisms and bioactive chemicals. Chitosan's film-forming and biodegradable qualities promote microbial inoculant adhesion to the seed surface, preserve them during storage, and allow for their progressive release into the rhizosphere following planting. This improves root colonization, nitrogen uptake, and early seedling vigour while simultaneously offering antimicrobial protection from seed-borne diseases (Kant *et al.*, 2025).

Application Methods

1. Seed Priming

Chitosan priming involves soaking seeds in a chitosan solution before sowing. Typical concentrations range from low mg/L to %-level solutions depending on the crop and objective (e.g., disease suppression vs. stress tolerance). Priming enhances water uptake, triggers defence responses, and prepares seeds for faster, more uniform germination (Godase, 2023).

2. Seed Coating and Film Formulations

Chitosan can be integrated into coating formulations or blended films. Coating with chitosan, alone or in combination with polymers like polyethylene glycol (PEG), improves physical protection, helps in controlled release of active agents, and can support microbial inoculants such as beneficial fungi (Vijaykumar *et al.*, 2024).

3. Nano-priming

Emerging approaches use chitosan nanoparticles (CSNPs) for seed priming. Nanoparticles increase surface area and enhance interaction with seed tissues (Kant *et al.*, 2025).

Advantages of Chitosan Seed Treatment

- Eco-friendly and biodegradable, reducing reliance on synthetic chemical treatments (Zhang *et al.*, 2026).
- Broad spectrum of activity, including antimicrobial effects and stress tolerance enhancement (Shcherban, 2023).
- Compatibility with beneficial microbes, enabling integrated biological seed treatments (Zhang *et al.*, 2026).
- Improvement in seed vigour, germination, and early seedling growth across diverse crops (Godase, 2023).

Challenges

Despite encouraging results, chitosan-based seed treatments have various practical obstacles that prevent their widespread implementation. The majority of research has been undertaken in controlled laboratory or greenhouse environments, leaving a substantial gap between experimental results and field validation. Chitosan's efficiency varies according to crop species, ambient conditions, and formulation features, making uniform recommendations difficult to develop. Furthermore, there is a dearth of established techniques for dose optimization and formulation development. Economic feasibility is still questionable, as thorough cost-benefit assessments covering production, storage, and use are limited. Scalability, compatibility with existing seed processing methods, long-term stability, and shelf life are all issues that need to be investigated further (Zhang *et al.*, 2026).

Conclusion

Chitosan has emerged as a flexible seed treatment agent with numerous advantages, including increased germination, disease resistance, and tolerance to abiotic challenges. Its biodegradability and beneficial effects on plant physiology make it a viable alternative to standard seed treatments. Ongoing research and developments in formulation technologies are broadening its use in modern agriculture.

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