CHITOSAN-BASED SEED COATING: A MULTIFUNCTIONAL PLATFORM FOR SEED ENHANCEMENT, STRESS RESILIENCE AND BIOTIC PROTECTION

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ABSTRACT
Chitosan-based seed coating is gaining attention as a biodegradable approach for integrating seed enhancement, stress tolerance and biological protection within a single treatment system. This review critically examines the role of chitosan in seed coating and related seed-treatment applications, with emphasis on germination and seedling establishment, root development, abiotic stress tolerance, pathogen suppression, insect pest management, defence activation and compatibility with beneficial microorganisms. Evidence from direct coating studies indicates that appropriately formulated chitosan can improve germination, seedling growth, antioxidant defence, membrane stability and in selected crops, yield. Complementary evidence from seed priming, soaking and other seed treatments further demonstrates potential for improving tolerance to salinity, drought and osmotic stress. The multifunctional effects of chitosan are associated with its film-forming capacity, cationic nature, antimicrobial activity and ability to elicit plant defence responses. Enhanced antioxidant and defence-related enzyme activities, reduced oxidative damage, improved ion homeostasis and maintenance of membrane integrity provide physiological evidence for these responses. However, chitosan performance is highly dependent on molecular weight, degree of deacetylation, concentration, formulation pH, coating thickness, additives, seed characteristics and environmental conditions. Excessive coating concentrations may restrict hydration and gas exchange, while unsuitable formulations can adversely affect germination or beneficial microbial viability. Although field studies have demonstrated improvements in crop performance and yield, field-scale evidence remains limited, particularly for formulation-specific coating systems. A critical distinction between true seed coating and other seed-treatment methods is therefore essential when interpreting the available evidence. Future research should focus on standardized characterization of chitosan, quantitative evaluation of coating properties and coating load, mechanistic understanding, formulation optimization, microbial compatibility, field validation, and assessment of scalability and economic feasibility. Overall, chitosan-based seed coating represents a promising multifunctional platform for sustainable seed management, but its broader agricultural application requires formulation-specific optimization and stronger field-based validation.

KEYWORDS: Chitosan; seed coating; seed enhancement; abiotic stress; biotic stress; plant defence; seed quality; sustainable seed management

1. INTRODUCTION
Seed quality represents one of the fundamental components of successful crop production because germination, seedling establishment and early root development determine the ability of plants to exploit available resources during subsequent growth. Seeds are exposed to several constraints immediately before and after sowing, including inadequate soil moisture, salinity, temperature fluctuations, unfavourable pH, oxidative stress and attack by soil- and seed-associated microorganisms and insect pests. These constraints can reduce germination, delay emergence, damage developing tissues and ultimately decrease crop establishment and yield. Seed treatment has therefore become an important component of modern crop production because it allows protective or stimulatory compounds to be delivered directly to the seed before sowing. Conventional seed-coating systems may contain synthetic pesticides, fungicides, polymers, dyes, nutrients or other additives that improve seed handling and provide protection during establishment. Although these materials can be effective, increasing dependence on chemical seed treatments has raised concerns regarding environmental contamination, phytotoxicity and resistance development in target

organisms. Biopolymer-based seed-treatment systems have consequently attracted increasing attention as alternative or complementary approaches.

Chitosan is particularly interesting in this context because it combines film-forming characteristics with biological activity. It is a carbohydrate biopolymer obtained primarily through deacetylation of chitin, which occurs naturally in crustacean shells, insect cuticles and fungal cell walls. Deacetylation increases the proportion of free amino groups along the polymer chain and contributes to the cationic characteristics of chitosan under acidic conditions. These properties are associated with film formation, antimicrobial activity and biological elicitation. When applied to seeds, chitosan can form a layer around the seed surface and thereby modify the immediate microenvironment of the seed. At the same time, chitosan may interact with microorganisms and plant tissues. Consequently, a chitosan coating has the potential to perform several functions simultaneously, including physical coverage of the seed, suppression of selected microorganisms and stimulation of physiological or defence-related responses in the developing plant.

The effectiveness of chitosan, however, should not be interpreted as universal. The selected studies demonstrate considerable variation according to crop, concentration, molecular characteristics, formulation and application method. Direct coating of soybean seeds improved germination, plant growth and yield, whereas excessive concentrations in corn reduced germination-related parameters and seedling development (Zeng et al., 2012; Zacharias et al., 2024). Similarly, chitosan-containing multilayer coatings maintained the viability of selected beneficial microorganisms under some formulations but negatively affected radicle emergence under others (Szemruch et al., 2024). An important consideration in interpreting the literature is the distinction between true seed coating and other forms of seed application. Direct seed coating involves deposition of a defined material on the seed surface, generally producing a film or coating layer that remains associated with the seed during handling, storage and at least part of the early imbibition period. In contrast, seed priming, soaking and immersion expose the seed to chitosan but do not necessarily result in formation of a persistent coating. These methods can induce physiological and biochemical responses that are highly relevant to seed enhancement, but they should not automatically be interpreted as evidence that the same response would occur through a physical coating.

Several studies in the available literature used priming, soaking, immersion or general seed treatment rather than a persistent coating (Ali et al., 2025; Hameed et al., 2014; Mahdavi & Rahimi, 2013; Odat et al., 2021; Martínez González et al., 2015; Liu et al., 2022; Al-Omairi & Al-Hilfy, 2021; Choudhary et al., 2017; Boonlertnirun et al., 2008). These studies are particularly valuable for understanding physiological responses to chitosan under salinity, osmotic stress and other constraints. Nevertheless, their findings are considered supporting evidence in this review rather than direct evidence of the performance of a persistent seed coating. Direct coating studies are therefore given greater emphasis when discussing coating performance, while priming and related treatments are used to strengthen the physiological and mechanistic interpretation.

This distinction is especially important because the physical properties of a coating can independently influence seed hydration, gas exchange and surface protection. A primed seed and a coated seed may therefore experience different exposure kinetics even when the same chitosan concentration is used. Clear differentiation among these application methods improves the scientific interpretation of the available evidence and prevents overextension of results obtained from one seed-treatment technology to another. The objective of this review is to critically integrate the available evidence on chitosan-based seed coating for seed enhancement, abiotic-stress resilience and biotic protection, with particular emphasis on germination, seedling establishment, root development, antioxidant responses, ion homeostasis, pathogen suppression, insect protection and compatibility with beneficial microorganisms. The review also examines the formulation and seed-related factors that determine coating effectiveness and identifies major challenges and research priorities for translation from laboratory studies to practical agricultural applications.

2. Chitosan: Origin, Preparation and Properties for Seed Coating

2.1 Origin and preparation of chitosan

Chitosan is produced primarily through the deacetylation of chitin. Chitin is a naturally occurring structural polysaccharide found in crustacean shells, insect cuticles and fungal cell walls. Deacetylation removes acetyl groups from the polymer chain and increases the proportion of free amino groups. These amino groups can become protonated under acidic conditions, giving chitosan a cationic character.The physicochemical and biological behaviour of chitosan depends strongly on its molecular characteristics, particularly molecular weight and degree of deacetylation. Chitosan should therefore not be regarded as a chemically uniform material. Hirano et al. (1990) demonstrated differences in chitinase induction among chitosan, oligosaccharides, carboxymethyl chitosan and depolymerized forms, indicating that structural characteristics influence biological activity.

Preparation conditions are also important because chitosan has limited solubility in neutral water and is commonly formulated under acidic conditions. Mahdavi and Rahimi (2013), for example, used low-molecular-weight chitosan with a degree of deacetylation above 75% prepared in 1% acetic acid and adjusted to pH 6 before seed application. In a direct corn-coating study, chitosan was formulated with acetic acid and glycerol and adjusted to approximately pH 4.7 before coating and drying (Zacharias et al., 2024). Thus, concentration alone is insufficient to describe a chitosan coating. Molecular weight, degree of deacetylation, solvent, pH, viscosity, additives and drying conditions can influence film formation and biological response.

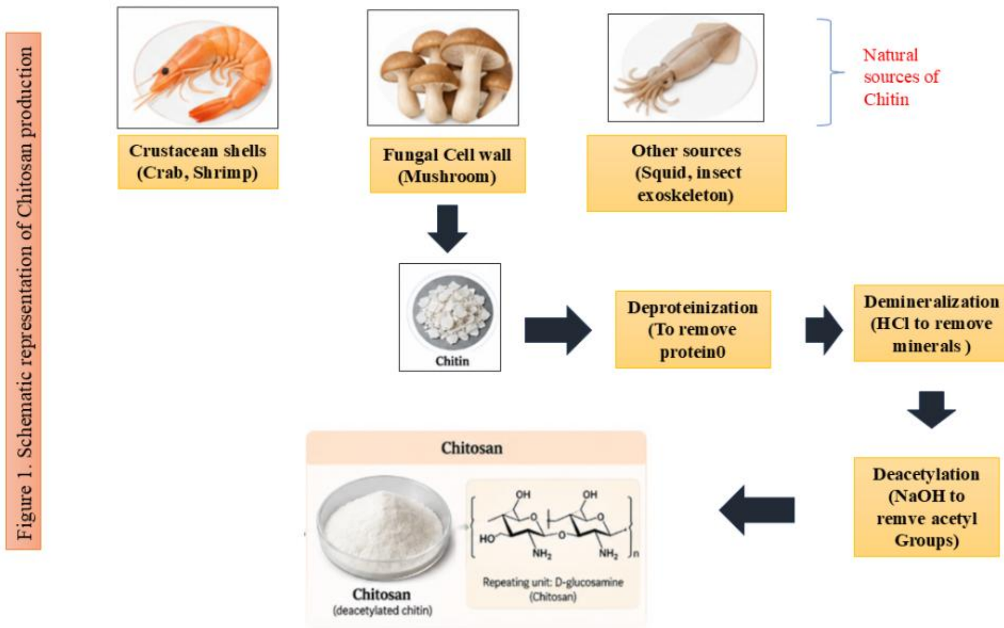

Figure 1. Schematic representation of Chitosan production.

2.2 Film-forming properties

One of the most important characteristics of chitosan for seed coating is its film-forming capacity. A useful coating must establish sufficient contact with the seed surface while avoiding excessive thickness that could restrict water or oxygen movement. The corn study of Zacharias et al. (2024) demonstrated this balance clearly. Increasing chitosan concentration improved coating coverage and produced thicker and more uniform films, but excessive concentrations negatively affected germination-related parameters and seedling growth. Thus, maximizing coating deposition is not necessarily desirable.

The ideal coating should provide sufficient surface coverage, adhesion and protection while maintaining permeability required for seed hydration and respiration. Film thickness, coating load per seed and drying conditions should therefore be considered important formulation parameters.

2.3 Cationic and antimicrobial properties

Chitosan becomes positively charged under acidic conditions because of protonation of its amino groups. This cationic character facilitates interaction with negatively charged components of microbial cell surfaces. Such interactions can alter membrane permeability and contribute to leakage of cellular constituents. This provides a mechanistic basis for the antimicrobial activity reported against several fungal organisms (Pabón-Baquero et al., 2015; Khaled & Alobaidi, 2023). However, antimicrobial activity is not uniform across all organisms. Zacharias et al. (2024), for example, reported suppression of Penicillium spp. but not significant control of Aspergillus and Fusarium under the tested coating conditions. Therefore, chitosan should be considered a potentially useful antimicrobial coating component rather than a universally effective fungicide.

2.4 Defence-eliciting properties

Chitosan can also function as an elicitor of plant defence responses. Hirano et al. (1990) demonstrated stimulation of chitinase activity in seeds of radish, soybean, milk-vetch and rice coated with chitosan derivatives. The magnitude of the response differed among crops and chitosan forms. The stimulation of chitinase and other defence-associated enzymes provides a biological explanation for some pathogen-suppression responses. However, increased enzyme activity should not automatically be interpreted as proof of a complete resistance pathway. The available evidence supports the view that chitosan can modulate defence-associated responses, while the relative contribution of individual pathways remains dependent on crop, formulation and stress conditions.

3. Chitosan-Based Seed Coating for Seed Enhancement and Abiotic-Stress Tolerance

3.1 Germination and seedling establishment

Improvement of germination and early seedling establishment is one of the most consistently reported benefits of chitosan-based seed application. Direct coating of soybean seeds with 1–5% chitosan improved germinability, germination percentage and germination index, with the 5% treatment producing more than 90% germination in the study of Zeng et al. (2012). The improvement was accompanied by enhanced plant height, dry matter production and root development. Under field conditions, the same study reported an approximately 20% increase in yield with the 5% coating compared with the untreated control. Wheat also provides direct evidence for beneficial effects. Chitosan coating improved germination, root length and root activity and increased the activities of superoxide dismutase, peroxidase and catalase while reducing malondialdehyde accumulation (Zeng & Luo, 2012). Improved chlorophyll status and an approximately 13.6% increase in yield were also reported.

Evidence from maize indicates that chitosan can influence seedling performance under stressful conditions. Lizárraga-Paulín et al. (2011) observed beneficial effects of chitosan application at the seedling stage under drought, moisture and pH-related stress conditions. However, the corn study of Zacharias et al. (2024) provides an important counterpoint. Increasing chitosan concentration did not continuously improve seed performance. Higher concentrations reduced germination speed and emergence-related indices as well as seedling height and shoot dry matter. The authors associated these effects with formation of a thicker physical barrier. These observations demonstrate that chitosan exhibits a concentration-dependent response. The optimum concentration should therefore be established using germination percentage, germination rate, emergence, seedling growth and coating characteristics rather than by selecting the highest concentration solely on the basis of antimicrobial activity.

3.2 Root development and early seedling vigour

Root development is particularly important during establishment because the root system determines the capacity of young plants to acquire water and nutrients. Soybean coated with chitosan showed improved root development and overall plant growth (Zeng et al., 2012), while wheat treated with chitosan demonstrated increased root length and root activity (Zeng & Luo, 2012). Supporting evidence is also available from bitter gourd under salinity. Seeds treated with 0.04% chitosan produced greater root and shoot growth and higher fresh and dry biomass than untreated seeds under 50 mM salinity (Ali et al., 2025). Several mechanisms may contribute to these responses, including modification of the seed microenvironment, changes in hydration and stimulation of physiological processes associated with growth and stress adaptation. However, a single molecular mechanism cannot be assigned uniformly to all crops. The evidence more strongly supports an association between chitosan exposure, improved physiological status and enhanced root development.

3.3 Antioxidant defence and oxidative-stress regulation

Abiotic stress frequently causes excessive accumulation of reactive oxygen species, resulting in oxidative damage to membrane lipids, proteins and other cellular components. Chitosan-treated seeds have demonstrated enhanced antioxidant capacity in several studies. Chitosan-coated wheat exhibited increased superoxide dismutase, peroxidase and catalase activities together with reduced malondialdehyde accumulation under drought-related conditions (Zeng & Luo, 2012). Bitter gourd provides additional evidence under salinity. Treatment with 0.04% chitosan increased superoxide dismutase activity by approximately 54.3% compared with salinity alone and increased peroxidase and catalase activities (Ali et al., 2025). The treatment also reduced electrolyte leakage by approximately 36%, suggesting improved membrane stability. The physiological interpretation is that enhanced antioxidant enzyme activity may help maintain redox balance during stress. Superoxide dismutase converts superoxide radicals into less reactive products, while catalase and peroxidase contribute to hydrogen peroxide detoxification. However, chitosan should be described as a modulator or elicitor of antioxidant defence rather than as a direct antioxidant that simply neutralizes all reactive oxygen species.

3.4 Salinity tolerance and ion homeostasis

Salinity is one of the major abiotic constraints addressed in the selected literature. Salt stress affects germination, water relations, membrane stability, photosynthesis and ion balance. In bitter gourd, 0.04% chitosan produced 72.215% final germination under 50 mM salinity compared with 37% in the salinity-only treatment (Ali et al., 2025). Root and shoot growth and biomass were also improved. The same study demonstrated changes in ion accumulation. Chitosan treatment reduced sodium accumulation by up to 31.25% relative to salinity alone and improved potassium and calcium status under the tested conditions (Ali et al., 2025). These responses are physiologically relevant because excessive sodium accumulation can interfere with cellular metabolism, whereas potassium and calcium contribute to enzyme activity, osmotic regulation and membrane stability.

Chitosan-treated bitter gourd plants also showed changes in relative water content and osmotic potential. These findings suggest that seed treatment may contribute to osmotic adjustment and maintenance of cellular water status, although the pathways linking early seed exposure to later plant responses require further investigation. Supporting evidence is available from ajowan, common vetch and rice. In ajowan, 0.2% chitosan improved germination under salinity (Mahdavi & Rahimi, 2013). Chitosan treatment of rice improved growth and altered biochemical stress indicators under saline conditions (Martínez González et al., 2015). Common vetch also showed improved germination and early growth following chitosan priming under salinity (Odat et al., 2021). Because these studies used priming or seed treatment rather than persistent coating, they should be regarded as supporting evidence for chitosan-mediated salinity tolerance rather than direct evidence of coating effects.

3.5 Water and osmotic stress tolerance

Water deficit and osmotic stress interfere with seed hydration and cellular water balance and can severely restrict germination and seedling growth. Wheat provides direct evidence that chitosan coating can improve performance under water-related stress. Zeng and Luo (2012) reported improved germination, root development and antioxidant enzyme activity together with improved crop yield. Supporting evidence from Hameed et al. (2014) demonstrated that chitosan priming improved wheat germination and seedling growth under polyethylene glycol-induced osmotic stress. Chitosan treatments improved final germination percentage, germination energy, vigour and seedling growth while reducing mean germination time. Since the latter study involved priming rather than coating, its results should not be interpreted as evidence for a physical chitosan film. Instead, the study demonstrates that seed exposure to chitosan before stress can induce physiological changes that persist during early seedling development.

3.6 Photosynthetic and physiological responses

The effects of chitosan are not restricted to germination. In wheat, chitosan coating was associated with improved chlorophyll status and subsequent crop performance (Zeng & Luo, 2012). Rice seedlings grown under saline conditions showed improved growth and changes in biochemical indicators following chitosan treatment (Martínez González et al., 2015). In bitter gourd, 0.04% chitosan partially improved chlorophyll-related responses under salinity, although the magnitude of response differed among concentrations (Ali et al., 2025). The combination of reduced electrolyte leakage, enhanced antioxidant activity and improved ion balance suggests that maintenance of membrane integrity may be an important component of chitosan-mediated stress tolerance. Such responses are relevant to seed coating because preservation of membrane function during early imbibition and emergence can support establishment under adverse conditions.

4. Chitosan-Based Seed Coating for Biotic-Stress Management

4.1 Antifungal activity and pathogen suppression

One of the strongest biological rationales for chitosan seed coating is its antimicrobial activity. Direct evidence from Jatropha curcas demonstrates substantial antifungal activity. Pabón-Baquero et al. (2015) reported that chitosan concentrations of 0.5–4 mg mL^{-1} inhibited mycelial growth of phytopathogenic fungi. At 4 mg mL^{-1}, inhibition reached approximately 98.7% for Fusarium equiseti and 92.3% for Curvularia lunata. Chitosan also inhibited sporulation and spore germination, while seed treatment improved germination under pathogen-associated conditions. The corn coating study provides additional evidence under a true coating system. Zacharias et al. (2024) found that an optimized chitosan formulation reduced Penicillium spp. while maintaining physiological seed quality. However, the formulation did not significantly control Aspergillus or Fusarium under the tested conditions. This variation demonstrates that chitosan should not be regarded as a broad-spectrum fungicide. Antimicrobial effectiveness depends on fungal species, concentration, molecular characteristics, formulation and environmental conditions.

The tomato study by Benhamou et al. (1994) provides complementary evidence for chitosan-induced resistance against Fusarium oxysporum f. sp. radicis-lycopersici. Chitosan seed treatment, particularly when combined with substrate treatment, reduced disease development and root lesions. Histological and biochemical observations indicated deposition of phenolic compounds and defence-associated structural changes. These findings illustrate two complementary modes of action: direct effects on the pathogen and induction of host defence.

4.2 Induction of plant defence responses

Chitosan can function as an elicitor of plant defence. Hirano et al. (1990) coated radish, soybean, milk-vetch and rice seeds with chitosan derivatives and measured chitinase activity. Chitosan coating stimulated chitinase activity, although the response varied among crops and chemical forms. Chitinases can contribute to defence against fungal pathogens because they degrade chitin-containing fungal structures. Therefore, increased chitinase activity following seed coating provides evidence that chitosan can activate defence-associated biochemical responses.

Further evidence is provided by Khaled and Alobaidi (2023), who observed enhanced activities of chitinase, β-glucanase, peroxidase, polyphenol oxidase, phenylalanine ammonia-lyase and catalase following chitosan seed treatment against tomato root wilt caused by Sclerotinia sclerotiorum. Chitosan also inhibited fungal growth in vitro. The combined evidence suggests that chitosan can provide both direct antimicrobial effects and host-mediated defence activation. Nevertheless, increased activity of individual enzymes should not be interpreted as proof of a universal signalling pathway. The magnitude and duration of defence activation require further validation, particularly under field conditions.

4.3 Insect pest management

Evidence for insect management is more limited than evidence for fungal suppression. Zeng et al. (2012) evaluated chitosan-coated soybean seeds against Agrotis ypsilon, soybean pod borer and soybean aphid. At 5% chitosan, antifeedant rates were approximately 82.89%, 87.24% and 80.21%, respectively. The same treatment improved germination, plant growth and yield. These findings demonstrate crop-specific potential for insect deterrence. The antifeedant effect may result from changes in seed or plant acceptability, surface characteristics or plant biochemical responses. However, the available evidence is insufficient to establish a universal insecticidal mechanism. Chitosan should therefore be described as having potential antifeedant or insect-protective activity rather than as a broad-spectrum insecticide.

4.4 Nematode management

The evidence base for nematode management is comparatively limited. Ibrahim and Kurniawati (2020) evaluated chitosan seed treatment for management of Aphelenchoides besseyi and reported that 0.25% chitosan was effective under the tested conditions without adversely affecting germination. Because the study used seed treatment or immersion rather than a conventional film-forming coating, it provides supporting rather than direct evidence for chitosan coating. Further research is needed to determine whether persistent seed-surface chitosan coatings can provide protection against seed-transmitted or early soil-associated nematodes.

4.5 Compatibility with beneficial microorganisms

Integration of beneficial microorganisms with polymeric seed coatings represents an important development in seed technology. Chitosan may function as one component of multilayer coatings containing microbial inoculants, but compatibility cannot be assumed. Szemruch et al. (2024) evaluated soybean seed coatings containing sodium alginate, chitosan, Trichoderma harzianum and Bradyrhizobium japonicum. Selected formulations maintained microbial viability during storage. However, some chitosan/talc formulations negatively affected radicle emergence, germination and seedling growth. Acidic chitosan did not adversely affect Bradyrhizobium under the tested conditions but inhibited Trichoderma. These results demonstrate that microbial compatibility depends on formulation, pH, concentration and microorganism identity. The objective should therefore not be simply to combine multiple biological agents within a single coating. Instead, multilayer systems should be designed to maintain microbial viability while preserving seed physiological quality.

4.6 Integrated biotic protection

The available evidence indicates that chitosan may provide multiple forms of biotic protection through complementary mechanisms. Direct antimicrobial activity can restrict fungal growth, while induced defence can increase the capacity of seedlings to respond to infection. In soybean, antifeedant effects additionally indicate potential against selected insect pests. The strength of evidence, however, is not uniform. Fungal suppression and defence activation are supported by several studies, whereas insect and nematode evidence remains comparatively limited. Therefore, chitosan should be considered a multifunctional biological coating component rather than a universal substitute for all chemical seed protectants.

5. Factors Affecting the Effectiveness of Chitosan Seed Coating

5.1 Chitosan concentration

Concentration is one of the most important determinants of coating performance. The soybean study demonstrated strong biological responses at 5% chitosan, while wheat showed an optimum around 0.8% in the reported coating study (Zeng et al., 2012; Zeng & Luo, 2012). Corn, however, demonstrated that concentrations above the optimum range could reduce germination and seedling growth (Zacharias et al., 2024). The concentration-dependent response reflects a balance between biological stimulation and physical barrier formation. Low concentrations may provide inadequate coverage, whereas excessive concentrations may generate films that restrict water and oxygen movement. Consequently, optimum concentration must be established separately for each crop and formulation.

5.2 Molecular weight and degree of deacetylation

Molecular weight and degree of deacetylation influence solubility, charge density, viscosity, film formation and biological activity. Chitosan with a higher degree of deacetylation contains a greater proportion of available amino groups and may therefore exhibit stronger cationic interactions under acidic conditions. However, no single molecular specification can be considered universally optimal. Hirano et al. (1990) demonstrated differential biological responses among chitosan derivatives, oligosaccharides and depolymerized forms. Mahdavi and Rahimi (2013) explicitly characterized their material as low-molecular-weight chitosan with more than 75% deacetylation. Future seed-coating studies should therefore report molecular weight and degree of deacetylation routinely.

5.3 pH and formulation chemistry

Chitosan is generally dissolved under acidic conditions, making pH an important formulation parameter. The pH can influence chitosan solubility, charge characteristics, film formation and microbial compatibility. In microbial-containing seed coatings, pH may determine whether beneficial organisms survive. Szemruch et al. (2024) demonstrated that acidic chitosan affected Trichoderma viability differently from Bradyrhizobium. Thus, formulation pH should be evaluated alongside concentration when biological inoculants are included.

5.4 Film thickness and coating uniformity

A useful coating must provide adequate and uniform coverage while maintaining sufficient permeability for germination. In corn, lower concentrations produced incomplete coverage, whereas higher concentrations produced thicker films (Zacharias et al., 2024). The biological optimum therefore lies between inadequate surface protection and excessive barrier formation. Because seeds undergo rapid hydration after sowing, coating thickness can influence the rate of water absorption and gas exchange. Future studies should therefore quantify film thickness, surface coverage and coating load rather than reporting concentration alone.

5.5 Plasticizers and other coating components

Plasticizers can modify the mechanical and physical characteristics of chitosan films. Glycerol was incorporated into the corn coating formulation evaluated by Zacharias et al. (2024). The optimized formulation maintained seed physiological quality while reducing Penicillium spp. Multicomponent coatings may also contain sodium alginate, talc, microbial inoculants or other active ingredients. Such combinations may improve functional performance but can also create interactions that affect seed quality. The biological compatibility of each component must therefore be evaluated rather than assuming that the combination will be beneficial.

5.6 Seed characteristics and crop species

Seed surface properties can influence coating adhesion, penetration and biological response. Hirano et al. (1990) observed differences in chitinase responses among crop species. Seed size, surface roughness, chemical composition, permeability and seed-coat structure may all affect coating behaviour. Consequently, a concentration that performs well on soybean cannot automatically be transferred to maize, wheat or vegetable seeds. Seed-specific formulation optimization is therefore essential.

5.7 Target pathogen or pest

Antimicrobial performance is organism-specific. Chitosan strongly inhibited F. equiseti and C. lunata in Jatropha-associated experiments (Pabón-Baquero et al., 2015), whereas the corn coating formulation reduced Penicillium but did not significantly control Aspergillus and Fusarium (Zacharias et al., 2024). The same principle applies to insects. The strong antifeedant activity observed in soybean demonstrates potential against selected pests but does not establish equivalent efficacy against unrelated insect species. Target-specific efficacy testing should therefore be an essential component of future studies.

5.8 Environmental and storage conditions

The performance of seed coatings is ultimately determined under storage and field conditions. Temperature, relative humidity, soil moisture, salinity, pathogen pressure and microbial community structure can influence coating behaviour. Arif et al. (2023) reported that chitosan-wax and chitosan-nanoparticle coatings helped maintain soybean seed quality during six months of storage. The treatments reduced deterioration-associated parameters such as moisture increase, respiration, malondialdehyde and electrical conductivity while maintaining germination and vigour. These results expand the potential role of chitosan from seed establishment to seed storage. However, storage performance should be evaluated separately from field performance because a coating that preserves seed quality during storage may behave differently after hydration and exposure to soil microorganisms.

6. Challenges and Prospects for Chitosan-Based Seed Coating

6.1 Challenges and limitations

Despite promising results, several limitations currently restrict the broader application of chitosan-based seed coating. The first is the lack of standardization among chitosan materials. Studies use different molecular weights, degrees of deacetylation, concentrations, solvents, pH conditions and additives, making direct comparison difficult. A reported chitosan concentration does not provide sufficient information to reproduce a coating unless the molecular characteristics and formulation conditions are also described. The concentration-dependent nature of the response is another limitation. Chitosan is not inherently beneficial at every concentration. The corn study demonstrated that increasing chitosan concentration can improve coating coverage while simultaneously reducing germination speed and seedling performance (Zacharias et al., 2024). Likewise, the soybean microbial-coating study showed that some formulations negatively affected radicle emergence and seedling growth (Szemruch et al., 2024). Another important limitation is the difference between laboratory, greenhouse and field evidence. Some of the strongest physiological responses have been obtained under controlled stress conditions, whereas field environments contain interacting stresses and biological communities. The distinction between coating and priming is also critical. Several studies demonstrating stress tolerance used priming or soaking rather than actual coating. These studies provide valuable evidence of chitosan-induced physiological responses but cannot be used to claim that a physical coating necessarily produces the same effect.

6.2 Formulation optimization and coating characterization

Future research should establish standardized characterization and reporting of chitosan. Every seed-coating study should ideally report molecular weight, degree of deacetylation, concentration, solvent, pH, viscosity or relevant film properties, coating method, drying conditions and coating mass per seed. Future work should also investigate the relationship between coating structure and seed physiology. Coating thickness, water absorption, oxygen permeability, adhesion and degradation should be evaluated together with germination and emergence. Rather than selecting the highest concentration that produces the strongest antimicrobial effect, researchers should identify the formulation that provides adequate protection without restricting germination.

6.3 Integrated and multilayer coating systems

Greater attention should be given to integrated formulations. The demonstrated compatibility of selected chitosan formulations with Bradyrhizobium and Trichoderma indicates potential for combining biopolymers with beneficial microorganisms (Szemruch et al., 2024). However, microbial viability and seed physiological quality must be evaluated simultaneously because the same formulation can be beneficial for one organism and inhibitory for another. Multilayer coating technologies may provide a useful strategy for physically separating incompatible components. A chitosan layer could provide surface protection, while another layer could carry microbial inoculants, nutrients or other compatible active ingredients. The development of such systems should be guided by biological compatibility rather than by simply increasing the number of components.

6.4 Mechanistic understanding

Several studies have reported increased antioxidant and defence-associated enzyme activities following chitosan treatment. However, the sequence of biological events connecting a seed-surface coating to these responses is not yet fully resolved. Molecular, biochemical and physiological approaches should be combined to determine whether the observed responses result primarily from defence elicitation, changes in hydration, altered redox regulation, direct antimicrobial effects, microbial interactions or combinations of these processes. Mechanistic studies should also distinguish between responses directly demonstrated in experiments and mechanisms proposed from the known properties of chitosan.

6.5 Field validation and agronomic performance

Field-scale evaluation is essential for determining whether physiological responses observed under controlled conditions translate into agronomic benefits. Chitosan coating should be tested under different soil types, moisture regimes, salinity levels and pathogen pressures, with measurements extending from germination and emergence to final yield. Field studies in soybean and wheat demonstrate that agronomic benefits are possible, including reported yield increases following chitosan coating. However, the number of field studies remains considerably smaller than the number of laboratory and controlled-environment studies. Future experiments should therefore include replicated field trials over multiple environments and seasons.

6.6 Commercialization, economics and regulatory considerations

For agricultural adoption, biological efficacy alone is insufficient. Commercial development will require evaluation of coating equipment, processing speed, coating load per unit seed, drying energy requirements, storage stability, material cost and compatibility with existing seed-treatment infrastructure. The availability and consistency of chitosan raw material must also be considered. Because chitosan is derived from biological sources, variation in molecular characteristics may affect formulation reproducibility. Environmental degradation and regulatory requirements should also be assessed before large-scale commercialization. A successful coating technology should demonstrate not only biological effectiveness but also economic feasibility, operational practicality and environmental acceptability.

6.7 Opportunities for sustainable seed management

The biodegradable nature and biological activity of chitosan provide an opportunity to develop seed-treatment systems that combine crop establishment with biological protection. The possibility of simultaneously improving germination, stimulating antioxidant defence, suppressing selected pathogens and deterring selected insect pests makes chitosan attractive for integrated seed management. Chitosan may therefore be especially valuable when used as a component of an integrated formulation rather than as a complete replacement for every conventional treatment. For example, chitosan could serve as a polymeric matrix for selected biological agents, nutrients or compatible active compounds. However, the formulation should be designed according to the biological requirements of the seed and associated microorganisms. The available evidence indicates that multifunctionality should arise from rational formulation rather than simply increasing the number of components.

7. CONCLUSION

Chitosan-based seed coating represents a promising approach for integrating seed enhancement, stress resilience and biological protection within a biodegradable coating system. The selected studies demonstrate that appropriately formulated chitosan can improve germination, seedling establishment, root development and physiological performance while providing protection against selected fungal pathogens and insect pests.

Direct coating studies in soybean, wheat, maize and other crops provide evidence for improvements in seed and plant performance. Supporting evidence from priming, soaking and related seed treatments further demonstrates the potential of chitosan to improve tolerance to salinity and osmotic stress. However, these application methods should not be considered equivalent because their physical and physiological interactions with seeds differ. The biological effects of chitosan arise from the interaction of its physical and biological properties. Its film-forming ability can provide surface protection, while its antimicrobial activity and capacity to stimulate defence-associated responses may contribute to pathogen suppression. Enhanced antioxidant enzyme activity, improved membrane stability, altered ion

balance and activation of defence enzymes provide physiological and biochemical explanations for several of the reported benefits.
At the same time, chitosan performance is strongly dependent on concentration, molecular weight, degree of deacetylation, formulation pH, coating thickness, additives, seed characteristics and environmental conditions. Excessive coating concentrations may form physical barriers that delay germination and reduce seedling development, while inappropriate formulations may compromise beneficial microorganisms. The current evidence therefore supports chitosan as a multifunctional component of advanced seed-coating systems, rather than as a universally effective replacement for all chemical seed treatments. Its greatest potential lies in combining physical coating, seed enhancement, stress-response modulation and selected forms of biotic protection within a single biodegradable platform. For broader agricultural application, future studies should prioritize standardized characterization of chitosan, quantitative evaluation of coating properties and coating load, mechanistic investigation, crop-specific formulation optimization, microbial compatibility, field-scale validation, storage stability, economic feasibility and environmental assessment. With these developments, chitosan-based seed coating has considerable potential to contribute to sustainable seed management and improved crop establishment under increasingly challenging biotic and abiotic environments.

Table 1. Effects of chitosan-based seed coating and seed treatments on crop performance and stress tolerance

Crop	**Application**	**Major response**	**Target stress / biotic factor**	**Reference**
Wheat (Triticum aestivum)	Seed coating	Improved seedling growth, protective enzyme activities and drought tolerance	Drought stress	Zeng & Luo (2012)
Wheat (Triticum aestivum)	Seed priming	Improved germination and seedling growth under osmotic stress	Osmotic stress	Hameed et al. (2014)
Maize (Zea mays)	Seed coating	Improved seed performance and seedling growth at appropriate concentrations; excessive concentrations were inhibitory	Abiotic stress / seed performance	Zacharias et al. (2024)
Maize (Zea mays)	Seed treatment	Improved seed germination, growth and enzyme activity	Seedling establishment	Choudhary et al. (2017)
Maize (Zea mays)	Seed treatment	Improved germination and early seedling responses under abiotic stress	Abiotic stress	Lizárraga-Paulín et al. (2011)
Rice (Oryza sativa)	Seed treatment	Improved seedling growth under saline conditions	Salinity stress	Martínez González et al. (2015)
Rice (Oryza sativa)	Field application / seed-related treatment	Improved crop growth, yield and seed quality	Crop performance	Boonlertnirun et al. (2008)
Soybean (Glycine max)	Seed coating	>90% germination and approximately 20% higher yield; antifeedant activity against selected insect pests	Seed performance / insect pests	Zeng et al. (2012)
Soybean (Glycine max)	Seed coating	Delayed seed deterioration and helped preserve seed quality during storage	Seed deterioration / storage	Arif et al. (2023)
Cowpea (Vigna unguiculata)	Seed treatment	Improved growth, yield and seed quality	Crop performance	El-Tanahy et al. (2012)
Common vetch (Vicia sativa)	Seed priming	Improved germination and early growth under saline conditions	Salinity stress	Odat et al. (2021)
Bitter gourd (Momordica charantia)	Seed treatment	Improved germination; enhanced SOD activity, reduced electrolyte leakage and Na^{+} accumulation	Salinity stress	Ali et al. (2025)
Tomato (Solanum lycopersicum)	Seed treatment	Induced systemic resistance and enhanced protection against Fusarium crown and root rot	Fungal disease	Benhamou et al. (1994)

Tomato (Solanum lycopersicum)	Seed priming	Upregulated defence enzymes and improved protection against root wilt	Fungal disease	Khaled & Alobaidi (2023)
Jatropha (Jatropha curcas)	Seed treatment	Suppressed growth of Fusarium equiseti and Curvularia lunata and supported seed germination	Fungal pathogens	Pabón-Baquero et al. (2015)
Ajowan (Carum copticum)	Seed priming	Improved germination and growth under saline conditions	Salinity stress	Mahdavi & Rahimi (2013)
Platycodon (Platycodon grandiflorus)	Seed soaking	Improved germination, growth, photosynthesis, resistance, yield and quality	Abiotic stress / plant performance	Liu et al. (2022)

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