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HARNESSING CHITOSAN FOR SEED QUALITY ENHANCEMENT AND STRESS RESILIENCE: CURRENT ADVANCES AND FUTURE PERSPECTIVES

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ABSTRACT

The rapidly growing global population has placed immense pressure on the agricultural production systems, necessitating a significant increase in agricultural output to meet rising demands. To achieve higher yields and ensure food security, farmers have increasingly relied on chemical fertilizers and pesticides. While these inputs have played a crucial role in boosting agricultural productivity, their excessive and indiscriminate use has led to a range of environmental and ecological consequences, exacerbating the impacts of climate change on agricultural production. To address these challenges, a shift toward sustainable agricultural practices is essential.

Seed is an important input and carrier of technology in agriculture. So, the quality of seeds plays a crucial role in attaining better plant growth and development throughout the crop cycle against biotic and abiotic stress. Even though the seed has its own capacity to germinate and grow, several challenges hinder this process. So, Chitosan is considered an eco-friendly alternative to synthetic seed treatments because it is biodegradable, non-toxic, and sustainable. Its use aligns with organic farming principles and can reduce reliance on chemical fungicides and pesticides.

1. INTRODUCTION

Robust seeds with enhanced seed vigour can moderate these challenges by ensuring consistent seedling growth across various environmental conditions. The rapid expansion of chitosan-based nanotechnology provides a robust framework for improving agricultural sustainability by facilitating the precise, sustained release of essential nutrients while minimising environmental loss (El-araby *et al*., 2024; Shelar *et al*., 2023). These innovative delivery systems leverage the biocompatible and biodegradable nature of chitosan to encapsulate inputs, thereby optimising bioavailability and reducing fertiliser runoff (Rosa *et al*., 2025). Furthermore, the integration of these materials into seed coating protocols serves as a multifunctional strategy to enhance germination vigour and shield seeds from soil-borne pathogens (Durgadevi *et al*., 2025; Nile *et al*., 2022). This review synthesises recent advancements in chitosan-based seed coating architectures, emphasising the molecular orchestration of germination and the intricate crosstalk between nanomaterials and the seed microbiome (Chakraborty *et al*., 2020). By critically examining the structural optimisation of nano-chitosan coatings, this paper evaluates how current engineering approaches can overcome existing limitations in stability and controlled release kinetics (Mujtaba *et al*., 2023; Sen & Das, 2024). Specifically, it highlights how chitosan nanoparticles mitigate the limitations of traditional, non-encapsulated fertiliser applications by providing a sustainable mechanism for nutrient management and stress resilience (Patyal *et al*., 2025).

2. LITERATURE REVIEW

Current research on chitosan-based seed treatments has transitioned from basic growth stimulation to sophisticated nano-enabled delivery systems, with studies demonstrating improved nutrient bioavailability and antifungal efficacy (Shelar *et al*., 2023; Verma *et al*., 2024). Specifically, nanopriming with chitosan-based carriers has been shown to induce vital physiological responses, such as the biosynthesis of auxin and the upregulation of key metabolic enzymes like α-amylase, which collectively bolster seedling vigour under both normal and abiotic stress conditions (Vinzant *et al*., 2023). Beyond these physiological enhancements, emerging investigations have begun to explore how these nanoparticulate systems interface with the seed microbiome, potentially modulating

rhizosphere colonisation patterns to further support early plant establishment (Mathew *et al*., 2026). Recent studies highlight that these biostimulant interactions extend to the dynamic recruitment of plant-growth-promoting rhizobacteria, which can significantly alter the metabolic activity of the seed-associated microbial community (Bartolucci *et al*., 2020).

3. Sources and characteristics of chitosan

Chitosan is one of the most abundant biopolymers or natural polysaccharides, deacetylated from chitin (β-(1→4)-linked D-glucosamine (deacetylated unit) and N-acetyl-D-glucosamine (acetylated unit) and is sourced from the shells of crustaceans like crabs, shrimp and lobsters, insect exoskeleton and cell wall of fungi (Riseh *et al*., 2024). Chitosan is typically white or off-white in colour, odourless and tasteless, and it is insoluble in water and organic solvents but dissolves in acidic solutions (pH<6.5) like glacial acetic acid (Li *et al*., 2019; Winarti *et al*., 2023) due to protonation of its amino groups. Numerous valuable properties of chitosan, including its low environmental toxicity, biodegradability (Allam *et al*., 2024), biocompatibility (Mukarram *et al*., 2023), hydrophilicity, positively charged and higher surface area (Riseh *et al*., 2024), can be utilised in vast agricultural applications.

4. Synthesis of chitosan

Industrially, chitosan is derived from chitin by a deacetylation process using alkali (40-50% NaOH) in which 80% of the acetyl group present in N-acetyl-D-glucosamine is removed, and β-1,4-D-glucosamine is formed during this process (Mukarram *et al*., 2023). Its properties and bioactivity depend on the three major factors: molecular weight, degree of deacetylation and polymerisation (Lyalina *et al*., 2023). The degree of acetylation affects the solubility and charge distribution (Namli *et al*., 2023); higher deacetylation increases positive charges and solubility in acidic conditions, whereas lower deacetylation improves the solubility in neutral and alkaline conditions.

Figure 1: Schematic representation of extraction and preparation of chitosan

5. Metanalysis

A statistical meta-analysis was not conducted; instead, the published literature indicates that chitosan consistently improves germination percentage, vigour index, root length, shoot length, antioxidant enzymes, photosynthetic traits, and disease suppression across multiple crops (Riseh *et al*., 2024). In cereals, the most common responses are improved germination and stronger seedling establishment (Guan *et al*., 2009; Sun *et al*., 2025). In legumes and vegetables, chitosan commonly enhances root growth, biomass accumulation, photosynthetic efficiency, and stress tolerance (Lyalina *et al*., 2023; Allam *et al*., 2024). Overall, the response depends on crop species, concentration, and application method (Sreelakshmi *et al*., 2024; Faqir *et al*., 2021).

A synthesis of the growing body of experimental literature reveals that the agronomic performance of chitosan depends strongly on the mode, timing and formulation of its application, rather than being a fixed, intrinsic property of the molecule itself. Comparative analysis of published trials across seed treatment, soil drenching and foliar spray approaches shows consistent trends in efficacy, target crop stage and practical constraints, even though the concentrations, molecular weights and crop species tested vary considerably between studies. Seed-applied chitosan formulations are most consistently associated with improvements in germination and early seedling vigour, whereas soil and foliar applications tend to act on later developmental and stress-response stages.

6. Application methods of chitosan in agricultural fields

Chitosan can be applied in agriculture through several distinct methods, and each of them targets different stages of crop production and plant pathogen interaction. The major application methods in current practice include foliar spray, soil amendment and seed treatment.

Table 1: The concise comparison table of chitosan application methods

Application methods	Stage of application	Advantages	Constraints/Limitations	Reference
Seed treatment	Pre sowing	Enhances germination, seedling vigour, early systemic resistance to pathogens	Species dependent, Risk of phytotoxicity at high concentrations	Sreelakshmi *et al*., 2024; Faqir *et al*., 2021
Soil drenching	Rhizosphere soil	Improves nutrient use efficiency, suppresses root pathogens, supports beneficial microbes	Requirement of high dose, leaching or adsorption in soil may reduce efficacy	Kashyap *et al*., 2015
Foliar spray	Vegetative or reproductive stage	Boosts photosynthesis, growth, systemic resistance and abiotic stresses	Repeated application, Sensitive to spray conditions (pH and Humidity)	Pandey *et al*., 2018

7. Role of chitosan mediated seed enhancement strategies

7.1. Role of chitosan in seed germination and vigour

Seed germination and seedling vigour are critical determinants of crop establishment, productivity and overall agricultural sustainability. Rapid and uniform germination ensures better crop stand establishment, efficient nutrient utilisation and improved tolerance against environmental stresses (Alex *et al*., 2024). Chitosan is extensively used as an active ingredient in seed priming, seed coating and nano-carrier systems to enhance seed physiological parameters through multiple mechanisms such as physiological and biochemical mechanisms (Kumari *et al*., 2026).

7.1.1. Enhanced imbibition rate and activation of hydrolytic enzymes

Seed imbibition is the first and most crucial step in seed germination during which dry seeds absorb water and resume their metabolic activities. Chitosan seed treatment has been widely reported to enhance water uptake and accelerate seed germination by improving seed hydration and membrane stability (Riseh *et al*., 2024). As a hydrophilic biopolymer, chitosan forms a thin semi-permeable layer around the seed surface, facilitating regulated water absorption while minimising imbibitional damage (Liaqat *et al*., 2026). This controlled and enhanced hydration stimulates respiration, ATP production and cellular signalling pathways required for germination. Chitosan functions as an elicitor molecule that is recognised by membrane receptors, triggering intracellular signalling cascades involving calcium ions, reactive oxygen species, nitric oxide and mitogen-activated protein kinases, which subsequently regulate hormone responsive gene expression (Gai *et al*., 2019).

One of the most important consequences of chitosan signalling is modulation of phytohormonal balance. Chitosan promotes gibberellin biosynthesis and its mediated responses (El-Bassiouny *et al*., 2023). Simultaneously, chitosan suppresses the inhibitory effects of ABA, which normally maintains seed dormancy and restricts germination. Increased gibberellin levels stimulate the aleurone cells surrounding the endosperm to synthesise and activate hydrolytic enzymes (Bethke *et al*., 1997). The increased hydration and metabolic activation induced by chitosan stimulate the production of α-amylase, protease and lipases, which hydrolyse starch, proteins and lipids into soluble metabolites required for embryo growth and radicle protrusion.

Recent studies have revealed extensive interactions between chitosan and phytohormone signalling networks. Chitosan interacts with multiple hormones including gibberellic acid, auxin, salicylic acid, jasmonic acid, ethylene and abscisic acid, thereby regulating plant growth, defence responses and stress adaptation.

Table 2: Chitosan-mediated enhancement of seed quality and seedling performance in different crops

Crop	Method of application	Chitosan concentration	Major effects	Reference
Maize	Seed priming for 60-64 hrs	0.50 %	Increased germination, enhanced root and shoot growth	Guan *et al*., 2009
Lettuce	Seed priming for 6 hrs	0.1 mg/ml	Earlier germination, enhanced root branching, increased fresh weight, improved chlorophyll and carotenoid contents	Lyalina *et al*., 2023
Pancratium	Seed nanopriming (8 hrs)	1 mg/ml	Improved germination percentage, seedling vigour, biomass accumulation and antioxidant activity	Allam *et al*., 2024
Soybean	Seed coating	Chitosan + Alginate/PEG coating	Improved plant establishment, nodulation and seed yield when combined with rhizobial inoculation	Jarecki (2021)
Soybean	Seed coating	Chitosan based multilayer	Maintained seed vigour and germination during storage, reduced	Winarti *et al*., 2023

		coating with Zn nanoparticles	lipid peroxidation and electrolyte leakage.	
Sesame	Film coating	0.1 %	Improved speed of germination, seedling vigour and seedling development	Godínez-Garrido *et al*., 2022
Bean	Film coating	0.1 %	Enhanced seedling establishment and vigour characteristics	

7.1.2. Molecular regulatory network activated by chitosan during seed germination

Chitosan acts as an elicitor by being recognised at the membrane level, which triggers calcium influx, ROS production, nitric oxide signalling, and MAPK cascades (Riseh *et al*., 2024), suppressing ABA-mediated dormancy. The downstream response includes α-amylase activation and reserve mobilisation, which support germination and early growth. These signals alter hormone balance by promoting gibberellin and auxin pathways while suppressing ABA-mediated dormancy. The downstream response includes α-amylase activation and reserve mobilisation, which support germination and early growth.

At the molecular level, chitosan perception and downstream signalling in germinating seeds follow a coordinated regulatory cascade that begins with recognition of chitosan oligomers by membrane-localised receptor-like kinases embedded in the plasma membrane of embryo and aleurone cells (Chakraborty *et al*., 2020). Ligand binding activates an immediate influx of calcium ions into the cytosol, and this calcium signature is decoded by calcium-dependent protein kinases that relay the signal to downstream mitogen-activated protein kinase cascades (Deng *et al*., 2025). In parallel, chitosan perception triggers a transient burst of reactive oxygen species and nitric oxide, both of which act as secondary messengers that amplify the transcriptional response rather than causing oxidative damage at the low concentrations typically used in seed treatment (Mukarram *et al*., 2023).

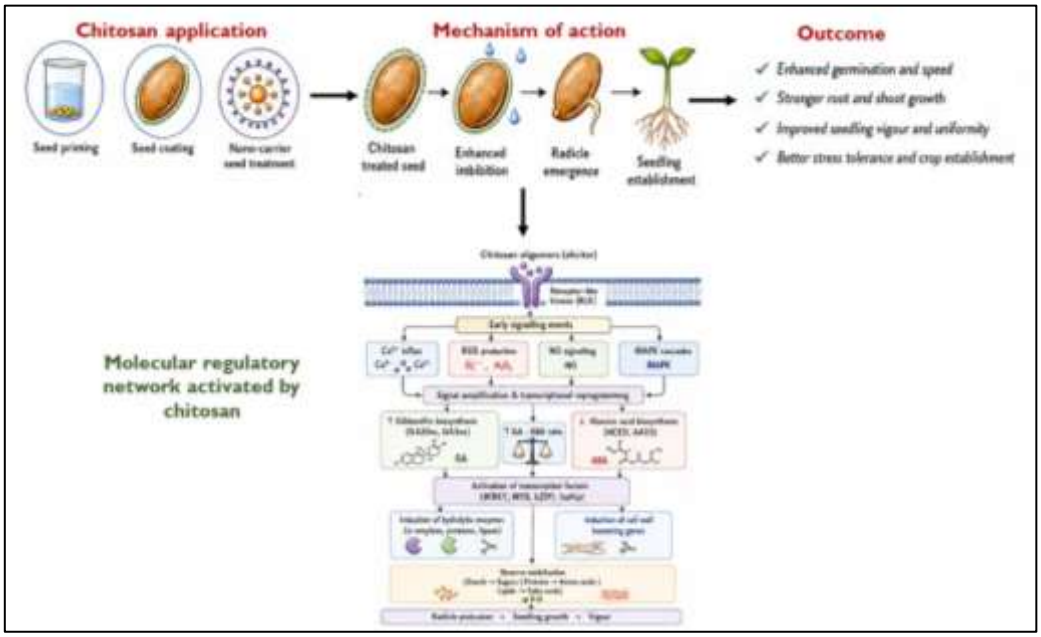

Figure 2: Chitosan applications and molecular mechanisms underlying enhanced seed germination and seedling vigour

These signalling events converge on the reprogramming of hormone biosynthesis genes, most notably upregulation of gibberellin biosynthetic genes alongside downregulation of abscisic acid biosynthesis and signalling components, shifting the GA: ABA ratio in favour of germination. Downstream transcription factor families, including WRKY, MYB and bZIP-type regulators, are activated as part of this network and, in turn, induce the expression of hydrolytic enzyme genes such as α-amylase, protease and lipase, along with cell-wall loosening genes that facilitate radicle protrusion (Wang *et al*., 2025). Chitosan-responsive transcriptomic studies further indicate coordinated activation of genes linked to chloroplast biogenesis even at the germination stage, suggesting that the molecular network initiated by chitosan perception extends beyond germination to prime the seedling for subsequent autotrophic growth (Xie *et al*., 2020).

7.1.3. Osmotic adjustment and water balance

Under drought and salinity stress, water uptake becomes limited due to reduced soil water potential. Chitosan promotes osmotic adjustment through the accumulation of compatible solutes such as proline, soluble sugars and

glycine betaine. These osmoprotectants maintain cellular turgor, stabilise proteins and membranes and facilitate water retention (Ahmed *et al*., 2024).

In maize, seeds primed with chitosan under low temperature stress showed an increased concentration of soluble sugars and proline, contributing to improved membrane stability and seedling growth (Guan *et al*., 2009). Similar effects were reported in rice and lentil under saline conditions (Panuccio *et al*., 2022).

7.1.4. Maintenance of membrane integrity

Environmental stresses often damage cell membranes, leading to increased permeability and leakage of cellular solutes. Chitosan reduces membrane injury by enhancing antioxidant protection and stabilising membrane structures. Consequently, treated seeds exhibit lower electrolyte leakage and reduced lipid peroxidation, maintaining normal metabolic activities during germination and seedling establishment (Guan *et al*., 2009).

7.1.5. Hormonal regulation

Chitosan influences phytohormonal signalling pathways that regulate stress responses. It modulates the balance between growth-promoting hormones such as gibberellins and auxin and stress-related hormones such as abscisic acid, salicylic acid and jasmonic acid (Sun *et al*., 2023). Chitosan oligosaccharides have been shown to alter the expression of genes involved in hormone biosynthesis and signalling, thereby improving stress adaptation and maintaining seedling growth under adverse conditions (Lu *et al*., 2024).

7.2. Effect of chitosan on seed viability during storage

Chitosan has emerged as an effective biopolymer for maintaining seed quality during storage owing to its film forming, antimicrobial, antioxidant and moisture regulating properties (Barik *et al*., 2024). Chitosan based seed coatings create a semi permeable protective layer around the seed surface, which reduces moisture fluctuations and slows down the deterioration process. The coating acts as a physical barrier against oxygen and pathogen invasion, thereby reducing respiration rate, lipid peroxidation and oxidative damage associated with seed ageing. Studies on soybean seeds demonstrated that chitosan and chitosan nanoparticle coating effectively maintained seed moisture content, protein content and lipid stability during storage while reducing malondialdehyde accumulation, a key indicator of membrane deterioration (Winarti *et al*., 2023). Chitosan coated seeds also exhibited lower electrical conductivity, indicating better membrane integrity and reduced solute leakage compared to untreated seeds. Furthermore, chitosan nanoparticles were found to suppress respiration and ethylene production during storage, thereby delaying physiological deterioration and prolonging seed viability. In bean and maize seeds, chitosan coating helps to maintain germination percentage up to 180 days without causing adverse effects on seed quality (Lyalina *et al*., 2023). This biopolymer also improved the retention and controlled release of fungicides, providing prolonged protection against storage fungi and seed borne pathogens. These combined effects contribute to enhanced seed vigour, higher germination, reduced aging related damage and extended shelf life during storage.

7.3. Seed protection against biotic and abiotic stress

Seed germination and seedling establishment are highly vulnerable stages in the plant life cycle. During this period, seeds are exposed to numerous biotic stresses such as fungi, bacteria, viruses, nematodes and insects as well as abiotic stresses including salinity, drought, flooding, chilling, heat and oxidative stress (Vijaykumar *et al*., 2024). These stresses impair water uptake, disrupt cellular metabolism, damage membranes, reduce reserve mobilisation, and ultimately decrease germination and seedling vigour. Chitosan has emerged as a promising natural biopolymer capable of protecting seeds against these adverse conditions through multiple physiological, biochemical and molecular mechanisms (Zhang *et al*., 2026).

7.3.1. Protection against biotic stress

Chitosan exhibits both direct antimicrobial activity and indirect induction of plant defence mechanisms (Zhang *et al*., 2026). The positively charged amino groups of chitosan interact with negatively charged components of fungal and bacterial cell walls, causing membrane disruption, leakage of intracellular constituents, inhibition of spore germination and suppression of pathogen growth (Mukarram *et al*., 2023). Studies in wheat demonstrated that chitosan treatment effectively reduced seed borne Fusarium infection, resulting in improved germination and seedling vigour. Chitosan treated seeds exhibited lower fungal transmission to emerging roots and enhanced resistance to disease development (Bhaskara Reddy *et al*., 1999).

Beyond its antimicrobial activity, chitosan acts as an elicitor of plant defence responses. Once recognised by receptors on the seed or plant cell surface, chitosan activates defence signalling pathways that stimulate the synthesis of pathogenesis related proteins and defence enzymes (Mukarram *et al*., 2023). Activities of phenylalanine ammonia lyase (PAL), polyphenol oxidase (PPO), peroxidase (POD), chitinase and β-1,3-glucanase increase significantly following chitosan treatment (Orzali *et al*., 2014; Khaled and Alobaidi, 2023). These enzymes contribute to pathogen resistance by degrading fungal cell walls, strengthening host tissues and promoting the accumulation of antimicrobial compounds. In wheat, chitosan induced resistance was associated with increased production of phenolic acids such as ferulic acid, caffeic acid, chlorogenic acid and gallic acid along with enhanced lignin deposition in seedling tissues. These compounds reinforce cell walls and create physical barriers against pathogen invasion (Bhaskara Reddy *et al*., 1999).

In pepper and tomato, chitosan treatment significantly increased chitinase and glucanase activities, leading to improved resistance against fungal pathogens and better seedling emergence under unfavourable conditions (Khaled and Alobaidi, 2023; Samarah *et al*., 2020). Enhanced accumulation of defence related enzymes and secondary metabolites contributes to systemic acquired resistance (SAR), enabling seedlings to withstand subsequent pathogen attack (Khaled and Alobaidi, 2023).

7.3.2. Protection against abiotic stress

Chitosan protects germinating seeds against environmental stresses primarily by improving antioxidant capacity, osmotic adjustment, membrane stability and hormonal regulation (Guan *et al*., 2009). Abiotic stresses such as salinity, drought, flooding and low temperature cause excessive production of reactive oxygen species (ROS) including superoxide radicals, hydrogen peroxide and hydroxyl radicals. Excessive ROS accumulation damages proteins, lipids, nucleic acids and cellular membranes, resulting in oxidative stress (Quitadamo *et al*., 2021).

Chitosan activates antioxidant defence systems by increasing the activities of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD) and ascorbate peroxidase (Jiao *et al*., 2024). These enzymes detoxify ROS and minimise oxidative damage (Pichyangkura & Chadchawan, 2015). In maize seedlings subjected to salinity stress, chitosan significantly increased antioxidant enzyme activities and reduced oxidative injury, leading to improved growth and stress tolerance (Jiao *et al*., 2024). Similarly, rice seedlings treated with chitosan exhibited reduced malondialdehyde accumulation, indicating lower membrane lipid peroxidation (Lu *et al*., 2024).

7.4. Chitosan - Seed microbiome interaction

Chitosan can alter seed-associated microbial communities by suppressing pathogens and favouring beneficial microbes in the rhizosphere and on the seed surface (Wang *et al*., 2024). This can improve PGPR colonisation, biofilm formation, and disease suppression while supporting microbial diversity around emerging roots (Kandasamy *et al*., 2024). Recent literature from 2023–2025 increasingly highlights microbiome-mediated benefits as an important part of chitosan's mode of action.

Seeds harbour a distinct and heritable microbiome that shapes the rhizosphere community of the emerging seedling and chitosan seed coatings are increasingly recognised as active modulators of this seed-associated microbial community rather than simply inert protective barriers (Nelson, 2018). Because of its polycationic nature, chitosan interacts selectively with microbial cell surfaces: pathogenic and saprophytic fungi with chitin-rich cell walls are often suppressed or structurally destabilised by chitosan, whereas many beneficial bacterial taxa, including plant growth-promoting rhizobacteria and antagonistic Bacillus and Trichoderma species are comparatively tolerant of or even stimulated by chitosan and its oligomeric derivatives.

This differential sensitivity allows chitosan coatings to reshape the composition of the seed and rhizosphere microbiome towards a community structure that favours plant health, an effect demonstrated through sequencing-based studies showing increased relative abundance of beneficial genera alongside a decline in pathogenic taxa such as Fusarium following chitosan-based treatments (Durgadevi *et al*., 2025). Chitosan seed coatings are also increasingly used as a delivery vehicle for beneficial microbial inoculants themselves, since the film matrix protects desiccation-sensitive bacteria and fungi during storage and improves their survival and colonisation capacity once the seed is sown indirectly promoting seedling growth through improved nutrient cycling and competitive exclusion of pathogens (Rocha *et al*., 2019). Chito-oligosaccharides released from the coating during early imbibition can further act as signalling molecules that shape microbial community assembly in the surrounding rhizosphere, indirectly promoting seedling growth through improved nutrient cycling and competitive exclusion of pathogens.

7.5. Functional role of chitosan in plant systems

Chitosan is recognized as a potent bio stimulant that positively influences plant growth and development through multiple physiological, biochemical and molecular mechanisms. Upon application as a seed treatment, foliar spray or soil amendment, chitosan enhances germination, root growth, shoot development, photosynthetic efficiency, nutrient uptake and overall plant productivity. Its growth promoting activity is associated with its ability to function as an elicitor molecule, activating signalling pathways that regulate plant metabolism and developmental processes (Kumari *et al*., 2025).

One of the primary effects of chitosan is the stimulation of root system architecture; chitosan enhances root elongation, lateral root formation, root branching and root biomass, thereby increasing the plant capacity for water and nutrient acquisition (Riseh *et al*., 2024). Enhanced root growth has been reported in wheat (Li *et al*., 2019), lettuce (Lyalina *et al*., 2023), rice (Moolphuerk *et al*., 2022), soybean (Mehmood *et al*., 2020), canola (Szemruch *et al*., 2024), sesame, bean (Godínez *et al*., 2022) and several horticultural crops (Timofeeva *et al*., 2024). Chitosan nanoparticles have been shown to increase indole-3-acetic acid (IAA) biosynthesis and transport while reducing IAA oxidase activity, leading to elevated endogenous auxin levels and accelerated root and shoot growth (Panichikkal *et al*., 2022).

Chitosan also promotes vegetative growth by increasing cell division and cell elongation. In rice seedlings, oligomeric chitosan significantly increased leaf and root fresh and dry weight through the regulation of gene expression networks associated with photosynthesis, carbohydrate metabolism and redox homeostasis. Proteomic analysis revealed that chitosan responsive proteins were predominantly linked to chloroplast functions, indicating

that chitosan enhances growth through coordinated interactions between nuclear and chloroplast genomes (Chamnanmanoontham *et al*., 2015).

A major contribution of chitosan to plant growth is its positive effect on photosynthesis. Chitosan treated plants exhibit higher chlorophyll content, carotenoid concentration, photosynthetic rate, stomatal conductance and water use efficiency (Vishnu *et al*., 2025). In *Platycodon grandiflorus*, seed soaking with 0.15-0.20% chitosan significantly improved leaf development, stem diameter, chlorophyll content, photosynthetic efficiency and biomass accumulation, resulting in enhanced plant vigour and productivity. Similarly, seed priming with chitosan hydrolysate increased chlorophyll and carotenoid accumulation in lettuce and promoted shoot and root biomass production (Liu *et al*., 2022).

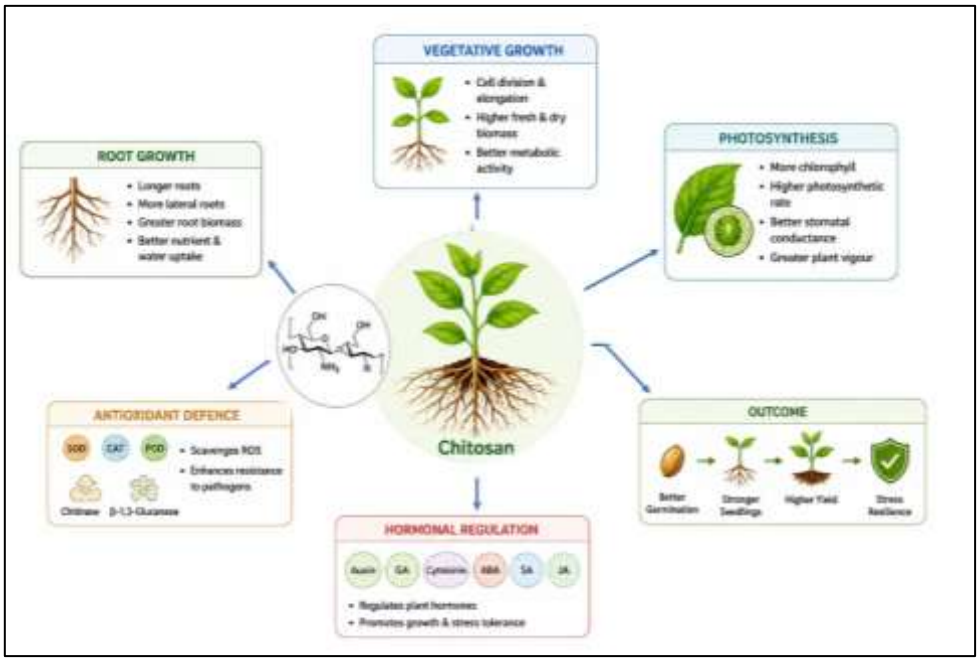

Figure 3: Functional mechanism of chitosan in plant growth and development

Chitosan further improves nutrient acquisition and utilisation by enhancing membrane permeability, root absorption efficiency and nutrient translocation. Increased uptake of nitrogen, phosphorus, potassium and micronutrients contributes to greater biomass production and yield formation (Chakraborty *et al*., 2022). In cowpea, increasing chitosan concentration significantly improved vegetative growth, pod yield, seed yield, protein content, carbohydrate accumulation and nutrient uptake, particularly when combined with inorganic fertilisation (Ahmed *et al*., 2024).

At the biochemical level, chitosan stimulates antioxidant defence systems including superoxide dismutase, catalase, peroxidase, chitinase and β-1,3-glucanase. These enzymes protect plants from oxidative stress generated during growth and environmental challenges (Jiao *et al*., 2024). Enhanced activities of chitinase and glucanase following chitosan treatment have been associated with improved resistance to fungal pathogens. Chitosan also influences plant growth through hormonal regulation (Khaled *et al*., 2023). It modulates the biosynthesis and signalling of auxins, gibberellins, cytokinin, abscisic acid, salicylic acid and jasmonic acid (Iglesias *et al*., 2019). Enhanced auxin and gibberellin activity promotes cell expansion, root development and biomass accumulation while optimised hormonal balance improves stress adaptation and developmental plasticity (Suwanchaikasem *et al*., 2024). Recent studies demonstrated that chitosan-based nanoparticles upregulated gibberellin-related genes and stimulated seedling growth, vigour and biomass accumulation in soybean (Steven *et al*., 2024).

7.6. Agronomic applications of chitosan

7.6.1. Controlled release nutrient delivery

Chitosan-based nanocarriers are increasingly used for controlled nutrient delivery because they can encapsulate fertilisers and release them gradually (Nandini *et al*., 2024). This improves nutrient use efficiency, reduces losses by leaching and volatilisation, and supports more precise supply of nitrogen and micronutrients such as zinc and iron (Nandini *et al*., 2025). Such systems are especially useful in seed coating and early seedling nutrition because they release nutrients when demand is highest.

Conventional fertilisers suffer from poor nutrient use efficiency because of leaching, volatilisation, fixation and microbial denitrification, resulting in substantial economic losses and environmental pollution such as eutrophication and greenhouse gas emissions (Nandini *et al*., 2025). Chitosan-based nanocarriers address this problem by encapsulating macro- and micronutrients within a polymeric matrix that releases the payload gradually rather than in a single pulse. In its nanoparticle form, chitosan is typically synthesised through ionotropic gelation

with polyanions such as sodium tripolyphosphate, which crosslinks the protonated amino groups of chitosan and traps nutrient ions within a compact, positively charged shell (Rosa *et al*., 2025). Because the amino groups remain pH- and enzyme-responsive, degradation of the chitosan shell by soil chitinases or changes in rhizosphere pH can further trigger targeted nutrient release when plant roots require it.

Chitosan nanoparticles loaded with nitrogen, phosphorus, potassium, zinc and other micronutrients have demonstrated the capacity to sustain nutrient availability for considerably longer than soluble fertiliser salts, reducing the frequency of reapplication and minimising losses through leaching (which supports biological nitrogen fixation. Collectively, these properties position chitosan-based controlled release systems as a next-generation alternative to conventional fertilisers, capable of simultaneously improving nutrient use efficiency and lowering the environmental footprint of crop nutrition management (El-Araby *et al*. 2024). Beyond passive diffusion, chitosan nanocarriers also promote nutrient uptake actively, since the polycationic shell stimulates root membrane permeability and enhances the activity of nutrient-related enzymes such as alkaline phosphatase, while inducing nodulation-related gene expression in legumes that supports biological nitrogen fixation (Shelar *et al*., 2023).

7.6.2. Crosstalk with other biostimulants

Chitosan often performs better when combined with other biostimulants because the effects are synergistic rather than isolated (Riseh *et al*., 2024). Synergy with seaweed extract, humic acid, fulvic acid, PGPR, *Trichoderma*, mycorrhiza, silicon, salicylic acid, and melatonin can improve root growth, nutrient acquisition, antioxidant defence and disease suppression (Wang *et al*., 2024; Kandasamy *et al*., 2024). These combinations are particularly valuable in sustainable agriculture because they enhance plant performance while reducing dependence on synthetic inputs (Riseh *et al*., 2024).

Chitosan rarely functions in isolation under field conditions; rather, it interacts, often synergistically, with other biostimulant classes such as humic substances, seaweed extracts and plant growth-promoting microorganisms (Gonçalves *et al*., 2025) and understanding this crosstalk is essential for designing effective seed treatment formulations. Combining chitosan with humic acid and beneficial bacteria such as *Bacillus subtilis* has been shown to produce effects greater than the sum of the individual components: humic acid improves the adsorption, dispersion and rhizosphere retention of both chitosan and the bacterial inoculant, while chitosan contributes antimicrobial protection and elicitor activity, together enhancing plant biomass and reshaping the rhizosphere microbial community towards beneficial taxa while suppressing soil-borne pathogens such as *Fusarium* (Qiu *et al*., 2025).

7.7. Factors influencing the effectiveness of coating

The effectiveness of chitosan seed coating depends on a combination of seed traits, chitosan properties, environmental conditions, and application practices. Seed species, seed size, testa thickness, surface roughness, and permeability strongly influence how well the coating adheres and how uniformly it covers the seed surface (Riseh *et al*., 2024). Coatings perform better on seeds that allow stable adhesion without blocking gas exchange, because excessive film buildup can delay imbibition and reduce emergence (Riseh *et al*., 2024; Zhang *et al*., 2026). Therefore, coating success is not universal; it must be optimised for each crop and seed lot rather than applied as a single standard treatment (Zhang *et al*., 2026).

Among chitosan-related factors, molecular weight, degree of deacetylation, viscosity, pH, and concentration are especially important because they determine film strength, antimicrobial activity, and release behaviour (Zhang *et al*., 2026; Krastev *et al*., 2025). Low to moderate concentrations often improve germination and vigour, while overly high concentrations may reduce emergence or cause phytotoxic effects in sensitive crops. The balance between film thickness and permeability is critical: a thicker layer may provide better protection and slower release, but too much thickness can interfere with oxygen diffusion and water uptake (Krastev *et al*., 2025). This is why coating formulations are often crop-specific and stress-specific, such as drought-tolerant formulations in sweet corn (Behboud *et al*., 2024) or multilayer systems that preserve microbial viability (Vijaykumar *et al*., 2024; Krastev *et al*., 2025).

Environmental conditions also shape coating performance because humidity, storage temperature, and storage duration influence coating stability and seed longevity. Under storage stress, chitosan coatings can reduce moisture fluctuation, oxidative damage, and pathogen invasion, helping preserve viability over time (Qian *et al*., 2026; Zhang *et al*., 2026). Application variables such as soaking time, drying method, spray uniformity, and coating sequence further affect final efficacy because they determine how much material remains on the seed and how evenly it is distributed. In practice, the best results are obtained when the coating is designed as a balanced system that matches seed physiology, field conditions, and the intended function of the treatment (Zhang *et al*., 2026).

7.8. Conclusion and future perspectives

Chitosan has emerged as a biodegradable, non-toxic, and multifunctional biopolymer that supports seed germination, seedling vigour, disease suppression, stress tolerance, nutrient delivery, and storage longevity. Its advantages arise from a combination of film-forming ability, antimicrobial action, elicitor activity, and controlled release behaviour, making it especially valuable in seed enhancement and sustainable crop establishment. Across

recent studies, chitosan coatings have consistently improved emergence, biomass accumulation, physiological quality, and resilience under both biotic and abiotic stress conditions. These findings confirm that chitosan is not simply a coating agent but a biologically active platform for precision seed technology.

Despite this considerable promise, several gaps continue to constrain the translation of chitosan-based seed treatments from experimental to commercial scale. Variability in raw material quality and inconsistent reporting of molecular weight and degree of deacetylation across studies make it difficult to compare results or establish universal application guidelines, and long-term, multi-location field trials evaluating chitosan seed coatings under diverse agroecological conditions remain comparatively scarce. The regulatory framework governing nanoscale chitosan formulations is also still evolving in many countries, creating uncertainty for commercial scale adoption.

Looking forward, several research directions appear particularly promising. Stimulus-responsive coating architectures that release nutrients or protective agents in response to specific environmental or physiological cues could substantially improve input use efficiency. Integration of multi-omics approaches will be valuable in fully elucidating the chitosan perception and signalling network across diverse crop species, while advances in green nanotechnology may resolve current challenges around the scalability and reproducibility of chitosan nanoparticle synthesis. Deeper investigation into chitosan-microbiome co-formulation strategies also holds potential to design next-generation biostimulant packages. Collectively, continued interdisciplinary research bridging polymer chemistry, molecular plant biology and agronomy will be essential to fully realise chitosan's potential as a cornerstone of sustainable, climate-resilient seed technology.

Statement and declaration

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Competing interest

The authors declare that they have no known competing interest that could have appeared to influence the work reported in this review paper.

Authors contributions

KM: Conceptualization, Literature search, Data curation, Writing - original draft, UR, VC, MS: Writing – review & editing, UR, MS, MS, BP: Visualization, Supervision

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