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Chitosan as a sustainable biopolymer in modern agriculture: A review

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Abstract

Global food security demands place enormous pressure on agricultural systems to enhance productivity, yet the environmental consequences of excessive synthetic fertilizer use have become increasingly alarming. These converging crises underscore an urgent scientific and policy need for eco-friendly, nutrient-efficient alternatives to conventional agrochemicals. Chitosan, a biodegradable biopolymer derived from the deacetylation of chitin, has emerged as a scientifically promising and environmentally responsible agricultural input. Its unique physicochemical attributes including biocompatibility, non-toxicity, cationic charge, and film-forming capacity render it uniquely suited to diverse crop production applications. This comprehensive review synthesizes recent advances in chitosan-based agricultural technologies, covering extraction methods, nutrient management, biostimulation, stress tolerance, and sustainable agriculture applications. The review also examines economic feasibility, regulatory frameworks, and future research priorities for chitosan in modern agriculture.

Keywords: Chitosan, sustainable agriculture, controlled-release fertilizer, nanofertilizer, biostimulant, nutrient-use efficiency, circular economy

Introduction

Sustainable agricultural production is facing increasing challenges due to rapid population growth, shrinking arable land, climate change, soil degradation, and the excessive use of synthetic agrochemicals. The global population is projected to reach 9.7 billion by 2050, requiring a 60-70% increase in food production (FAO, 2022). Simultaneously, climate change-induced weather extremes, including droughts, floods, and heatwaves, are threatening crop yields worldwide. The over-reliance on synthetic fertilizers has resulted in significant environmental degradation, with agricultural runoff contributing to approximately 30% of global greenhouse gas emissions from the agricultural sector (IPCC, 2023). These converging challenges necessitate the development of sustainable agricultural inputs that can maintain productivity while minimizing environmental footprints.

To meet the rising food demand, fertilizer consumption has increased substantially worldwide. In India, fertilizer use reached approximately 601 lakh metric tonnes (LMT) during 2023-24, yet nutrient-use efficiency remains low, with fertilizer nitrogen utilization ranging from only 15-30% in most cropping systems (Department of Fertilizers, Government of India, 2024) ^[11]. A significant proportion of applied nutrients is lost through leaching, runoff, volatilization, and fixation, resulting in economic losses and environmental problems such as water contamination, greenhouse gas emissions, and soil quality deterioration. Conventional fertilizers are associated with low nutrient use efficiency because of their rapid nutrient release and high chemical reactivity. The mismatch between nutrient availability and crop uptake results in considerable nutrient losses through leaching, volatilization, runoff, and soil fixation. According to Tandon, H. L. S. (2017), crops absorb only 10-20% of applied phosphorus, 30-60% of nitrogen, and 30-50% of potassium, whereas the remaining nutrients are lost, contributing to both economic inefficiency and environmental pollution. Therefore, there is an urgent need for sustainable agricultural inputs that can improve nutrient-use efficiency while minimizing ecological impacts.

Among the various approaches being explored, biopolymers have gained considerable attention

as environmentally friendly alternatives to conventional petroleum-based materials. Unlike synthetic polymers, biopolymers are derived from renewable biological resources and are generally biodegradable, biocompatible, and non-toxic. Major biopolymers used in agricultural applications include cellulose, starch, alginates, and chitin-based materials. Among these, chitosan has emerged as one of the most promising natural polymers because of its multifunctional properties and broad applicability in crop production systems.

Chitosan is produced through the partial deacetylation of chitin, the second most abundant natural polysaccharide after cellulose, and is commonly obtained from crustacean shells, insects, fungi, and other biological sources (Younes and Rinaudo, 2015) [65]. Owing to its unique physicochemical characteristics, including biodegradability, film-forming ability, chelating capacity, antimicrobial activity, and biocompatibility, chitosan has attracted significant interest in sustainable agriculture. It can act as a carrier material, protective coating, soil amendment, and plant biostimulant, thereby contributing to enhanced crop growth and productivity.

Recent studies have demonstrated that chitosan-based formulations improve nutrient availability and nutrient-use efficiency by regulating nutrient release and reducing losses through leaching and volatilization. Chitosan has also been widely investigated for the development of controlled-release fertilizers, nanofertilizers, hydrogels, seed coatings, and bioactive delivery systems. In addition to nutrient management, chitosan enhances plant defense responses, improves tolerance to abiotic and biotic stresses, suppresses plant pathogens, and contributes to postharvest quality preservation. These properties make chitosan a valuable component of sustainable farming systems aimed at reducing dependence on conventional agrochemicals.

This review presents a comprehensive overview of the recent advances in chitosan-based agricultural technologies, with particular emphasis on extraction methods, nutrient management, controlled-release fertilizers, nanofertilizers, plant growth promotion, stress mitigation, pest and disease management, postharvest applications, and circular economy aspects. The opportunities, limitations, economic feasibility, regulatory frameworks, and future prospects of chitosan in sustainable agriculture are also discussed.

Chitosan: origin, structure, and properties

natural sources of chitin and chitosan

Chitosan is a valuable amino polysaccharide obtained by the partial deacetylation of chitin, one of the most abundant naturally occurring biopolymers. The deacetylated derivative of chitin was first identified by Rouget in 1859, and the name chitosan was subsequently proposed by Hoppe-Seyler in 1894. Chemically, chitosan consists of D-glucosamine and N-acetyl-D-glucosamine residues linked through β -(1 $\rightarrow$ 4) glycosidic bonds, possessing reactive amino and hydroxyl functional groups that contribute to its diverse biological activities (Rinaudo, 2006) [51]. Chitin is a linear polysaccharide composed of β -(1 $\rightarrow$ 4)-N-acetyl-D-glucosamine units and occurs abundantly in crustacean shells, fungal cell walls, insects, and mollusks (Kou *et al.*, 2021) [34]. Chitin occurs naturally in three crystalline forms, namely α -, β -, and γ -chitin, which differ in molecular arrangement and source. Chitosan is produced by partial deacetylation of chitin under alkaline conditions. A degree of deacetylation above 50% is generally required for

classification as chitosan (Mukhtar *et al.*, 2021) [40].

Marine sources

In aquatic systems, the seafood-processing industry generates the dominant global supply of chitin and chitosan, primarily through utilization of crustacean shell wastes. Marine sources encompass shrimps, crabs, lobsters, krill, cuttlefish, squid pens, marine diatoms, and certain algae. Shrimp and crab shells remain the principal commercial feedstocks owing to their high chitin content approximately 30-40% in shrimp shells and 15-30% in crab shells combined with year-round industrial availability and well-established extraction protocols (Pakizeh *et al.*, 2021; Terkula Iber *et al.*, 2022) [26, 46]. Beyond chitin, these crustacean by-products are biochemically rich in proteins, carotenoid pigments, lipids, minerals, and bioactive compounds, positioning them as attractive raw materials for integrated biorefinery approaches. The valorization of such seafood-processing wastes into commercial chitosan simultaneously addresses industrial waste disposal concerns and supports resource recovery within a circular bioeconomy framework (Santos *et al.*, 2020) [52].

Terrestrial sources

Across terrestrial ecosystems, arthropods and insects represent a taxonomically diverse and largely underexplored reservoir of chitin. Species including silkworms (*Bombyx mori*), honeybees (*Apis mellifera*), beetles, termites, mosquitoes, and stick insects such as *Sipyloidea sipylos* and *Extatosoma tiaratum* contribute appreciable chitin yields from their cuticles and exoskeletons (Muñoz-Seijas *et al.*, 2026; Lin *et al.*, 2025) [37, 43]. Terrestrial crustaceans such as *Porcellio scaber* and *Armadillidium vulgare* similarly serve as secondary chitin reservoirs (Seidl *et al.*, 2012) [53]. Although terrestrial organisms are not currently exploited at commercial scale, their potential as sustainable, land-based chitin feedstocks has gained growing scientific interest within insect-based circular bioeconomy frameworks (Kee *et al.*, 2026; Lin *et al.*, 2025) [32, 37].

Microbial sources

The microbial world constitutes an increasingly significant and strategically important source of chitin and chitosan. Among fungi, representatives of Ascomycetes, Basidiomycetes, Deuteromycetes, and Zygomycetes contain chitin or chitosan concentrations of 2-65% of their dry cell wall mass, predominantly localized in cell walls, mycelia, and septa, with the notable exception of Oomycetes, which lack chitin entirely (Abo Elsoud and El Kady, 2019) [2]. "Other microbial contributors include chrysophyte algae, yeasts, spores of *Streptomyces* species, and certain ciliated protozoa (Herth *et al.*, 1977) [23]. Fungal-derived chitosan has attracted particular commercial attention as a non-crustacean alternative owing to its low mineral and protein contamination, batch-to-batch compositional consistency, reduced allergenicity risk, and suitability for vegan and halal-certified product applications (Pochanavanich & Suntornsuk, 2002; Nitschke *et al.*, 2011) [44, 50]. Collectively, the sustainable extraction of chitosan from these diverse biological waste streams spanning seafood processing residues, insect biomass, and fungal fermentation by-products not only reduces dependence on a single supply chain but also minimizes environmental burdens associated with biomass disposal, aligning chitosan production with broader objectives of waste valorization, pollution reduction, and the advancement of bio-based agricultural and industrial economies.

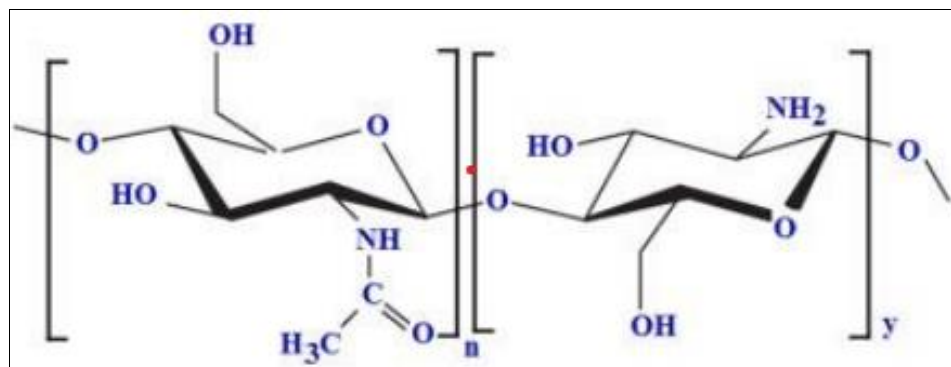


Fig. 1: Chemical structure of chitosan showing D-glucosamine and N-acetyl-D-glucosamine units linked by β-(1→4) glycosidic bonds (Source: Elieh-Ali-Komi *et al.*, 2016) ^[16].

Physicochemical properties of chitosan

Chitosan possesses a unique combination of physicochemical and biological properties that make it a highly versatile biopolymer for agricultural and other applications. Structurally, it consists of D-glucosamine and N-acetyl-D-glucosamine units linked by β-(1→4) glycosidic bonds, with amino groups at the C2 position and hydroxyl groups at the C3 and C6 positions that contribute to its high reactivity (Elieh-Ali-Komi *et al.*, 2016; Rinaudo, 2006) ^[16, 51]. The functional characteristics of chitosan are largely governed by its molecular weight and degree of deacetylation, which influence its solubility, viscosity, biological activity, and chemical reactivity (Mukhtar *et al.*, 2021) ^[40]. Chitosan exhibits high crystallinity and hydrophilicity and is insoluble in water and most organic solvents but readily dissolves in dilute acidic solutions due to protonation of its amino groups. This protonation imparts a strong cationic nature, enabling interaction with negatively charged molecules such as microbial cell membranes, soil colloids, and nutrient ions. Chitosan also possesses excellent chelating and complex-forming abilities, allowing efficient binding and delivery of micronutrients such as iron, zinc, copper, and manganese. Additional important physicochemical properties include high ionic conductivity, polyelectrolytic behavior, film-forming capacity, adsorption potential, and separation and filtration capabilities. Biologically, chitosan is biodegradable, biocompatible, non-toxic, bioactive, and environmentally friendly. It also exhibits antimicrobial, antioxidant, and elicitor activities that enhance plant growth, stimulate defense mechanisms, and improve resistance to biotic and abiotic stresses. The combined influence of molecular weight, degree of deacetylation, crystallinity, particle size, surface area, and source of extraction determines its overall performance and suitability for agricultural, environmental, biomedical, and industrial applications (Kou *et al.*, 2021) ^[34].

Chitosan extraction methods

Chitosan extraction can be carried out using both biological and chemical methods, typically involving three main steps: demineralization, deproteinization, and deacetylation. The chemical method is the most widely adopted for commercial production because of its rapid processing. However, biological extraction is gaining attention as a safer and more economical alternative, since it generates minimal effluents. Despite this advantage, its application remains largely limited to laboratory-scale studies.

Chemical extraction

The chemical method is the most common commercial approach for chitosan extraction, though it has environmental drawbacks

and may alter chitin properties (Varun *et al.*, 2017) ^[59]. The process typically involves demineralisation using dilute hydrochloric acid or other acids (sulfuric, formic, acetic, oxalic, nitric) to remove calcium carbonate, with optional decolourisation using sodium hypochlorite, acetone, or hydrogen peroxide to eliminate pigments like astaxanthin and β-carotene. Deproteinization is carried out with sodium hydroxide (0.125-5.0 M) at varying temperatures and durations, or alternatively with proteolytic enzymes such as trypsin or papain, though NaOH can also cause hydrolysis, molecular weight reduction, and partial deacetylation. The final step, deacetylation, uses concentrated alkalis (NaOH or KOH) to remove acetyl groups, producing amino groups (-NH₂), and requires a degree of deacetylation ≥75% for the material to be classified as chitosan. Modified processes have been reported, such as the use of calcium oxide for deproteinisation to bypass demineralisation in blue crab and shrimp shells (Lee *et al.*, 2017) ^[35], while fungal mycelia, which have low inorganic content, eliminate the need for demineralisation, offering a sustainable alternative source of chitosan.

Biological extraction

Biological extraction methods, including microbial fermentation and enzymatic processing, have been developed as eco-friendly and cost-effective alternatives to conventional chemical techniques for producing chitosan from crustacean by-products. In enzymatic extraction, enzymes are used to replace alkalis and high temperatures during the deproteinization and deacetylation steps, though the demineralization process remains similar to that of chemical methods.

The fermentation method for producing chitosan uses fungal mycelia, which naturally contain less inorganic matter, eliminating the need for demineralization. Fungal mycelia are subjected to alkaline treatment with 1M NaOH at 120°C for 15 minutes, followed by centrifugation and precipitation to yield chitosan (Winterowd *et al.*, 1995) ^[61]. Compared to crustacean-derived chitosan, fungal chitosan is of higher quality, showing improved deacetylation, viscosity, molecular weight distribution, and charge uniformity. Importantly, it is free of heavy metals like nickel and copper, making it safer and more stable. Fungal chitosan generally has a medium-low molecular weight (~1×10⁴ Da), while crustacean sources yield higher molecular weights (~1.5×10⁶ Da), increasing the demand for fungal-based chitosan as a sustainable alternative (Karamchandani *et al.*, 2025) ^[30].

Beyond fungal fermentation, biological extraction methods such as microbial fermentation and enzymatic processing are emerging as eco-friendly substitutes for harsh chemical techniques. Enzymatic deproteinization employs proteases from

fish viscera or microbes, while microbial fermentation utilizes proteolytic microorganisms (e.g., *Pseudomonas aeruginosa*, *Bacillus subtilis*, and *Serratia marcescens*) along with lactic acid bacteria for simultaneous deproteinization, demineralization, and deacetylation (El-Araby *et al.*, 2024) [12].

These biological methods yield chitosan with better quality and higher molecular weights than chemical extraction (Younes *et al.*, 2014) [64]. However, their large-scale application is limited by the high cost of purified enzymes, although microbial enzyme blends are being explored as a cost-effective alternative.

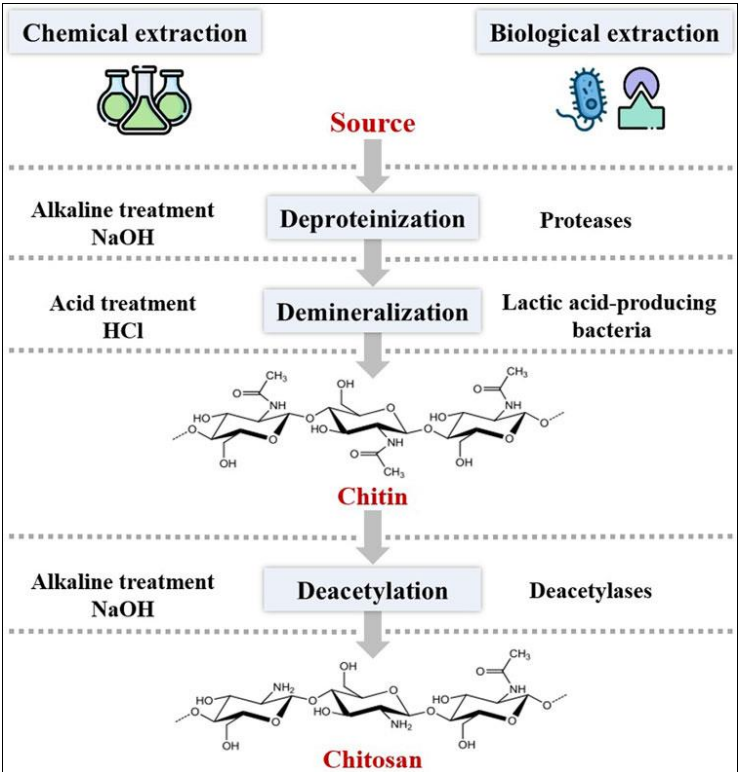


Fig. 2: Schematic representation of chemical and biological extraction methods for chitosan production (Source: El-Araby *et al.*, 2024) [12].

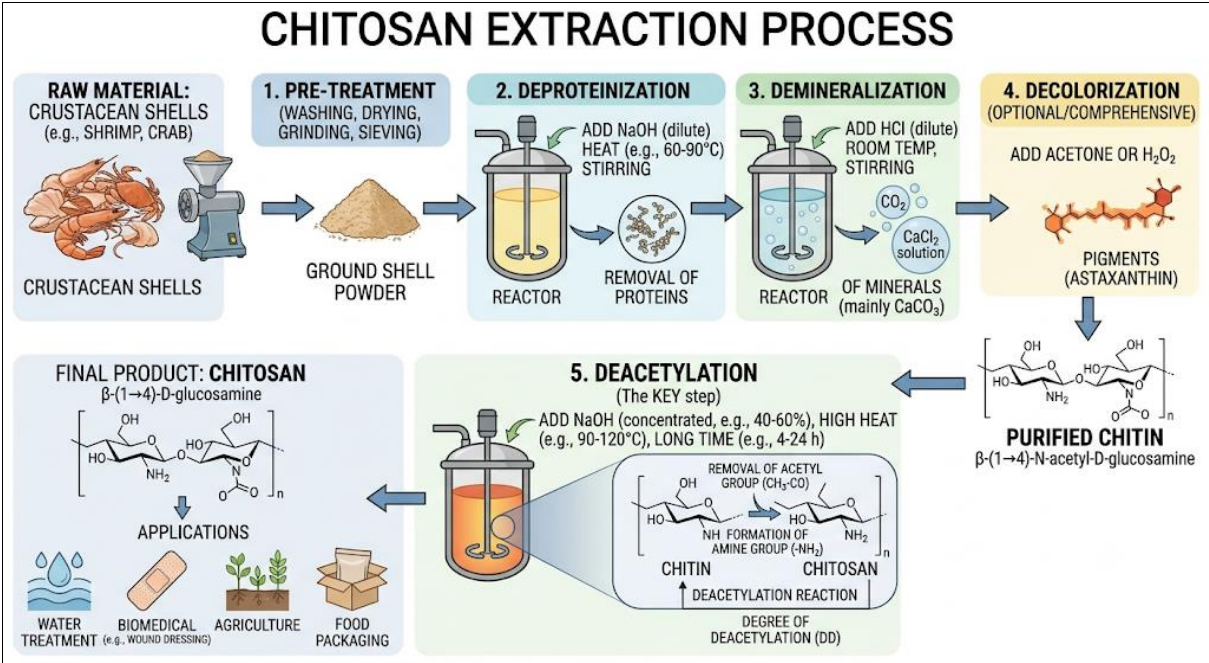


Fig 3: The figure shows the conversion of crustacean shells into chitosan through pre-treatment, deproteinization, demineralization, decolorization, and deacetylation steps.

Biological methods for chitosan extraction are eco-friendly but limited by high enzyme costs, strain specificity, and long processing times, restricting their large-scale use. In contrast, chemical extraction remains the dominant industrial method due to its efficiency, scalability, and ability to yield chitosan with high deacetylation and strong biological activity, despite its

environmental drawbacks (Çelebi *et al.*, 2026) [8].
Agricultural applications of chitosan
effect of chitosan as controlled-release fertilizers
Controlled-release fertilizers (CRFs) are designed to release nutrients gradually in synchronization with crop demand,

thereby improving nutrient-use efficiency and reducing nutrient losses. Chitosan has gained significant attention as a coating material for CRFs because of its biodegradable nature, porous structure, and excellent film-forming ability. Ma *et al.* (2023) developed chitosan microsphere-based controlled-release nitrogen fertilizers for Chinese cabbage cultivation. The study demonstrated enhanced seed germination, plant height, chlorophyll content, photosynthetic efficiency, and metabolite accumulation compared to conventional urea fertilizers. The controlled nutrient release from chitosan microspheres reduced nutrient losses and improved fertilizer efficiency.

Similarly, García-Ilizaliturri *et al.* (2025) reported that phosphorus fertilizers encapsulated with ultrasound-modified chitosan exhibited slower phosphate release and enhanced growth of *Arabidopsis thaliana* compared to conventional fertilizers. Chitosan-coated fertilizers therefore represent an eco-friendly strategy for improving nutrient delivery and reducing environmental contamination.

To enhance the efficiency of fertilizer and water resources, a novel chitosan-coated Compound Fertilizer with Controlled-release and Water-retention properties (CFCW) was developed. Elemental analysis and atomic absorption spectrophotometry revealed that the contents of nitrogen, phosphorus (expressed as P₂O₅), and potassium (expressed as K₂O) were 8.06%, 8.14% and 7.98% by weight, respectively. The findings suggested that these functions effectively as a slow-release fertilizer with superior water-retention capabilities (Wu and Liu, 2008).

Urea was encapsulated in chitosan microspheres using an emulsification process, followed by cross-linking with genipin, a natural cross-linker. Increasing the concentration of urea (1.0 g) led to a higher release rate, while higher concentrations of chitosan (0.5 g) and cross-linker concentration (0.75 mmol/g of chitosan) decreased the release rate (Hussain *et al.*, 2012) [25].

Chitosan-based hydrogels

Hydrogels are three-dimensional polymeric networks capable of retaining large amounts of water and nutrients. Chitosan-based hydrogels improve soil moisture retention and enhance nutrient availability under drought conditions.

Pandya and Mungray (2024) [47], developed chitosan-urea core-shell hydrogels using ionic gelation techniques. The hydrogels absorbed more than 100 times their weight in water and gradually released urea over an extended period. These formulations maintained soil moisture for several days and demonstrated potential for dryland agriculture. Pandya, J. *et al.*, (2024) [47], developed innovative chitosan-urea core-shell hydrogels for sustainable agriculture. Using an ionic gelation method, urea was incorporated into a κ -carrageenan core and coated with a chitosan shell to form five. Among them, CK-CU-10 showed the best performance, absorbing over 100 times its weight in water, releasing 70.4% urea over 10 days (90.5% total), and retaining 80% soil moisture for nine days without irrigation. These cost-effective hydrogels offer an eco-friendly solution for controlled fertilizer and water release, particularly suited to dryland farming.

The use of chitosan hydrogels in agriculture is particularly important in arid and semi-arid regions where water scarcity limits crop productivity. Their application enhances irrigation efficiency, reduces nutrient leaching, and improves plant growth under moisture stress.

Chitosan nanoparticles and nanofertilizers

Nanotechnology has expanded the potential applications of chitosan in agriculture. Chitosan nanoparticles possess high

surface area, enhanced reactivity, improved nutrient delivery and greater penetration into plant tissues.

Elshamy *et al.* (2019) [14], reported that nano chitosan NPK fertilizers significantly improved potato yield, tuber weight, dry matter accumulation, and nutrient uptake compared to conventional fertilizers. Interestingly, lower nanoparticle concentrations produced superior results, indicating higher fertilizer-use efficiency.

Li *et al.* (2019) [36], demonstrated that chitosan nanoparticles enhanced wheat seed germination and seedling vigour by regulating auxin biosynthesis and signaling pathways. Chitosan nanoparticles also improved chlorophyll content, protein accumulation, and root development.

Nano-chitosan systems are therefore promising tools for precision nutrient management and sustainable crop production.

Effect of chitosan-based hydrogels

Biopolymeric hydrogels are widely used globally, especially in agriculture, where they serve as carriers for nutrients and pesticides and act as water reservoirs. Chitosan-based hydrogels, in particular, enhance soil water retention and deliver agrochemicals effectively, making them valuable soil conditioners. These hydrogels support crop growth and productivity, especially under water-saving irrigation practices.

Pandya, J. *et al.*, (2024) [24], developed innovative chitosan-urea core-shell hydrogels for sustainable agriculture. Using an ionic gelation method, urea was incorporated into a κ -carrageenan core and coated with a chitosan shell to form five formulations (CK, CK-CU-2, CK-CU-5, CK-CU-7.5, CK-CU-10). Among them, CK-CU-10 showed the best performance, absorbing over 100 times its weight in water, releasing 70.4% urea over 10 days (90.5% total), and retaining 80% soil moisture for nine days without irrigation. These cost-effective hydrogels offer an eco-friendly solution for controlled fertilizer and water release, particularly suited to dryland farming.

Effect on crop production

Chitosan functions as an effective plant biostimulant, promoting growth and productivity across a wide range of crops. When applied foliarly at optimal concentrations, typically between 100 and 125 ppm, it can improve morphological characteristics such as plant height, leaf number, and total dry matter, while also enhancing yield components, including fruit number and size. In okra, chitosan application increased fruit yield by up to 27.9% compared with untreated plants (Mondal *et al.*, 2012) [39]. These growth-promoting effects have been associated with enhanced chlorophyll accumulation, photosynthetic efficiency, nutrient uptake, and nitrogen metabolism (Ullah *et al.*, 2026; Oppong-Sekyere *et al.*, 2026) [45, 58].

Field studies further indicate that chitosan can improve crop resilience under abiotic stress. Its application helps maintain relative leaf water content, regulate stomatal conductance, and preserve plant vigor under water-limited conditions (Wakchaure *et al.*, 2023) [60]. Nano-chitosan formulations may provide additional benefits by enabling more targeted nutrient delivery and strengthening plant tolerance to environmental stress (Ullah *et al.*, 2026) [58]. Because chitosan is biodegradable, biocompatible, and generally non-toxic, it represents a promising sustainable alternative to conventional agrochemicals for improving crop production in cereals, legumes, and vegetables (Oppong-Sekyere *et al.*, 2026) [45].

Abiotic and biotic stress tolerance

Chitosan is recognized as an effective biostimulant that

enhances plant tolerance to both abiotic and biotic stresses. Under abiotic stress conditions such as drought, salinity, temperature extremes, and heavy metal toxicity, chitosan improves photosynthetic efficiency, nutrient uptake, antioxidant enzyme activity, osmolyte accumulation, and water-use efficiency while reducing the accumulation of reactive oxygen species (ROS). It also activates stress-responsive signaling pathways involving abscisic acid (ABA), jasmonic acid (JA), and salicylic acid (SA), thereby improving plant adaptation to adverse environmental conditions (Khan *et al.*, 2002; Hadwiger, 2013; Mukhtar Ahmed *et al.*, 2020) ^[22, 33, 41].

Under biotic stress, chitosan functions as a potent elicitor by stimulating the production of phytoalexins, pathogenesis-related proteins such as chitinase and β -1,3-glucanase, proteinase inhibitors, callose deposition, lignin biosynthesis, and defense-related gene expression. Moreover, chitosan-induced accumulation of JA enhances plant defense responses against pathogens and insect pests while contributing to improved water regulation under stress conditions. Consequently, chitosan-based formulations enhance crop productivity, stress resilience, and disease resistance, making them promising tools for sustainable agriculture (Farouk and Ramadan, 2012; El Hadrami *et al.*, 2010; Pichyangkura and Chadchawan, 2015) ^[15, 49].

Effect on soil physical properties

Chitosan improves soil structure and physical properties through enhancement of aggregation, porosity, hydraulic conductivity, and water retention. Shaban *et al.* (2021) ^[55] observed that chitosan nanofertilizers significantly improved soil physical properties under saline conditions by reducing bulk density and increasing water-stable aggregates. Chitosan also stimulates beneficial microbial activity and root colonization by arbuscular mycorrhizal fungi (AMF). Amerany *et al.* (2020) ^[4] reported increased AMF colonization and improved nutrient uptake in tomato plants treated with chitosan.

A series of new soil conditioner systems were made by in-situ hydrogelation of chitosan by salicylaldehyde with urea fertilizer for both fertilization and water retention of soil. These formulations had high water absorbency (68 g/g), water holding capacity in soil (up to 154%) and an increase in the nitrogen content in soil of almost double, resulting in an almost 70% greater plant growth compared to that observed on the reference soil (Iftime *et al.*, 2019) ^[27].

These improvements contribute to enhanced soil fertility, water management, and overall crop performance.

Chitosan as a plant biostimulant

Chitosan functions as an effective plant biostimulant by enhancing physiological and biochemical processes in plants. Foliar application of chitosan improves chlorophyll synthesis, photosynthesis, nutrient assimilation, enzyme activity, and antioxidant defense systems. Wan Ahmad Sofian *et al.* (2022) demonstrated that foliar application of 200 ppm chitosan significantly increased growth and fruit yield of red chili under field conditions. Similarly, Rani and Viji (2023) observed enhanced growth parameters in Ashwagandha (*Withania somnifera*) following foliar application of chitosan. Under drought stress conditions, Farouk and Ramadan (2012) reported that foliar application of 250 mg L⁻¹ chitosan improved chlorophyll content, carbohydrate accumulation, nutrient uptake, and pod yield in cowpea plants. The ability of chitosan to stimulate plant metabolism and alleviate abiotic stress makes it a valuable component of sustainable crop production systems.

Plant defense and pest management

Chitosan acts as an elicitor molecule capable of inducing systemic acquired resistance in plants. It stimulates defense-related enzymes, phytoalexin synthesis, and antioxidant activity, thereby enhancing plant resistance against pathogens and environmental stresses.

Abdel-Aziz (2019) ^[1] reported increased antioxidant enzyme activities and total phenol content in broad bean seeds primed with chitosan nanoparticles. Chitosan nanoparticles also demonstrated strong antifungal activity against several soil-borne pathogens (El-Mohamedy *et al.*, 2019) ^[13].

In pest management, Chitosan induces systemic acquired resistance (SAR) in plants, enhancing their tolerance to various abiotic stresses (drought, salinity) and biotic stresses (pathogens) (Chouhan *et al.*, 2020), indirectly supporting nutrient assimilation under stress conditions. Selva Rani *et al.* (2022) ^[54] developed a chitosan-O-arginine formulation that effectively controlled diamondback moth larvae in cauliflower. The formulation exhibited high larval mortality and feeding deterrence comparable to commercial biopesticides. These findings highlight the potential of chitosan as a safe and eco-friendly alternative to synthetic pesticides.

Postharvest quality management

Chitosan applications improve crop quality, nutritional value, shelf life, and postharvest stability. Parvin *et al.* (2019) observed increased vitamin C, lycopene content, and fruit firmness in tomatoes treated with chitosan.

Chitosan coatings also reduce microbial spoilage and delay ripening in fruits and vegetables. Arun *et al.* (2024) ^[5, 6] reported that chitosan coatings significantly reduced fungal decay and extended shelf life in strawberries, bananas, and citrus fruits.

Similarly, irradiated chitosan coatings effectively preserved mango quality during storage by reducing weight loss, microbial growth, and nutrient deterioration.

Heavy metal toxicity mitigation and phytoremediation

Heavy metal contamination in agricultural soils due to industrial effluents, mining activities, and low-grade phosphate fertilizers presents a significant risk to food safety. Chitosan acts as an exceptional agent for soil detoxification and heavy metal immobilization due to its abundant primary amino and hydroxyl functional groups). These groups act as electron donors that form stable coordination complexes via chelation with toxic divalent and trivalent heavy metal cations such as cadmium, lead, nickel, and arsenic Gamage, A., & Zhang, Y. (2023) ^[21].

By binding these ions within the soil matrix, chitosan drastically lowers their bioavailability and prevents their uptake by plant roots. When heavy metals do cross the root barrier, exogenous chitosan applications upregulate the expression of phytochelatin synthase and metallothioneins, which sequester the toxic ions within vacuolar compartments (Nesta *et al.*, 2024). This structural sequestration limits the dangerous translocation of heavy metals from roots to the edible shoots and grains of agricultural crops.

Low-temperature chilling and cryo-stress alleviation

Cold and chilling stresses severely disrupt the cellular homeostasis of plants by inducing ice crystal formation, cell dehydration, and lipid peroxidation of plasma membranes. Exogenous application of low-molecular-weight chitosan mitigates cold injury by strengthening the plant's internal antioxidant buffering systems (Gao *et al.*, 2022). Chitosan

triggers a rapid increase in the activities of superoxide dismutase (SOD), guaiacol peroxidase (POD), and catalase (CAT), which neutralize the toxic superoxide radicals and hydrogen peroxide accumulated during cold exposure. Furthermore, chitosan acts as a metabolic signal that accelerates the accumulation of endogenous osmoprotectants, particularly proline, soluble proteins, and total soluble sugars (Abdel-Rahman *et al.*, 2024). These highly hydrophilic solutes stabilize the tertiary structure of cellular proteins and lower the freezing point of the cytoplasm, protecting vulnerable tissue from cellular membrane leakage and irreversible chilling necrosis.

Immobilization matrix for plant growth-promoting rhizobacteria (pgpr)

The open-field survival and functional efficacy of inoculated Plant Growth-Promoting Rhizobacteria (PGPR) are frequently compromised by indigenous soil microbial competition and fluctuating environmental factors. Because of its excellent porous structure, high biocompatibility, and non-toxic film-forming behavior, chitosan serves as an outstanding protective immobilization carrier for beneficial bioinoculants like *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Azotobacter chroococcum* (Pereira *et al.* 2023) ^[48]. When formulated as beads or liquid micro-encapsulations, chitosan shields the encapsulated PGPR from sudden desiccation, osmotic shock, and predatory soil protozoa. This protective microenvironment allows for the steady, sustained release of bacteria into the rhizosphere, facilitating dense root colonization. Studies at the Kerala Agricultural University (KAU) have demonstrated that utilizing chitosan-based carrier matrices for *Pseudomonas* co-inoculation significantly enhances the long-term survival of the bacteria in humid tropical soils, leading to enhanced solubilization of fixed soil phosphorus and sustained secretion of indole-3-acetic acid (IAA) (Anitha and Radhakrishnan, 2023).

Ultraviolet-b (UV-B) radiation damage amelioration

Depletion of the stratospheric ozone layer has increased the levels of solar ultraviolet-B (UV-B, 280-320 nm) radiation reaching crop surfaces, which damages photosynthetic machinery, impairs DNA replication, and disrupts thylakoid membrane proteins. Foliar applications of chitosan form an ultra-thin, semi-permeable biopolymeric film over the leaf cuticle that physically scatters a portion of incoming solar UV radiation (Nesta *et al.*, 2024). At the biochemical level, chitosan functions as an elicitor that activates the phenylpropanoid metabolic pathway. This pathway upregulates key operational enzymes, such as chalcone synthase (CHS) and phenylalanine ammonia-lyase (PAL), which drive the synthesis of UV-absorbing compounds like anthocyanins, flavonoids, and polyphenols within the epidermal layers (Sharma and Kumar, 2024). These compounds act as a natural internal sunscreen, absorbing harmful wavelengths before they reach the vulnerable photosynthetic mesophyll tissue.

Modulation of secondary metabolite biosynthesis

In the cultivation of medicinal and aromatic crops, the commercial value depends heavily on the concentration of secondary metabolites, such as essential oils, alkaloids, glycosides, and terpenoids. Chitosan serves as a highly effective elicitor that mimics pathogen attack signals without causing actual disease, shifting plant metabolic resources toward secondary defense pathways (Rani and Viji, 2023).

Katiyar *et al.* (2015) ^[31], confirms that chitosan treatment stimulates defense mechanisms and enhances production of secondary metabolites through activation of the phenylpropanoid pathway.

Chitosan-based smart delivery systems

Stimuli-responsive chitosan formulations

Recent advances have enabled the development of stimuli-responsive chitosan-based delivery systems that release nutrients or bioactive compounds in response to specific environmental triggers. pH-responsive chitosan hydrogels release their cargo under acidic conditions, which aligns with the rhizosphere acidification that occurs during nutrient uptake. Temperature-responsive chitosan formulations have been developed for controlled release in response to diurnal temperature variations (Chellathurai *et al.*, 2024) ^[19].

Enzyme-triggered release systems

Chitosan-based delivery systems can be engineered to incorporate enzymes that regulate nutrient release in response to biological activity. For instance, microcapsules containing urease within a chitosan matrix are designed to liberate nitrogen only when soil microbes activate the enzyme. This synchronization ensures that nutrient availability coincides with crop demand, thereby enhancing efficiency and reducing losses to the environment (DeGroot & Neufeld, 2001) ^[10]. By coupling nutrient release to microbial signals, such systems improve fertilizer use and minimize contamination risks.

Integration with precision agriculture technologies

Chitosan formulations combined with precision agriculture tools create new possibilities for site-specific nutrient delivery. When integrated with remote sensing platforms, IoT-enabled soil sensors, and drone-based application systems, these materials can be applied at variable rates in response to real-time crop and soil conditions (Iqbal, 2024) ^[29]. Such integration enhances nutrient efficiency, lowers ecological risks, and contributes to the sustainable intensification of farming practices.

Chitosan with microbial inoculants

Pairing chitosan with beneficial soil life, such as mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR), yields compounded benefits for agricultural output. For instance, applying crab-derived chitosan alongside the PGPR *Pseudomonas putida* on maize crops led to notable growth increases: 55.7% in leaf area, 31% in stem diameter, and 26.8% in plant height relative to untreated plants (Agbodjato *et al.*, 2026). Such combinations improve plant stress resilience, nutrient absorption, and root colonization. They also facilitate a steady distribution of microbial metabolites into the soil while prolonging the commercial viability and shelf life of microbial products.

Chitosan in the circular bioeconomy framework

Waste valorization

Producing chitosan from by-products like fungal fermentation, insect biomass, and seafood waste strongly supports circular economy models. Each year, the world generates roughly 6 to 8 million tonnes of crustacean shell waste, yet merely 20% to 30% of this material is actively repurposed (Yan *et al.*, 2023) ^[63]. Transforming these discarded shells into valuable chitosan not only curtails waste management expenses but also mitigates ecological harm and fosters economic growth in coastal regions.

Carbon footprint assessment

Assessment Analyses of life cycles (LCAs) reveal that sourcing chitosan from waste materials generates a notably smaller carbon footprint than manufacturing synthetic polymers. A foundational LCA utilizing primary data from European and Indian manufacturers pinpointed energy consumption and the creation of harsh chemicals (like NaOH and HCl) as the primary

environmental burdens of production (Muñoz *et al.*, 2018) ^[42]. By limiting nitrogen loss and boosting how efficiently plants use nutrients, fertilizers containing chitosan can cut greenhouse gas emissions by 35% to 45% relative to traditional options. Furthermore, contemporary biorefinery techniques allow for the step-by-step recovery of various beneficial compounds from crustacean shells, optimizing both resource use and profitability while curbing waste (Sustainable Chemistry One World, 2026) ^[57]. This comprehensive strategy tackles the historical neglect of by-products, promoting a circular biorefinery model that merges nutrient reuse, side-stream processing, and compound extraction.

Synergistic combinations

Chitosan with microbial inoculants

Pairing chitosan with beneficial soil life, such as mycorrhizal

fungi and plant growth-promoting rhizobacteria (PGPR), yields compounded benefits for agricultural output. For instance, applying crab-derived chitosan alongside the PGPR *Pseudomonas putida* on maize crops led to notable growth increases: 55.7% in leaf area, 31% in stem diameter, and 26.8% in plant height relative to untreated plants (Agbodjato *et al.*, 2026). Such combinations improve plant stress resilience, nutrient absorption, and root colonization. They also facilitate a steady distribution of microbial metabolites into the soil while prolonging the commercial viability and shelf life of microbial products.

Chitosan with plant growth regulators

Combining chitosan with plant growth regulators (PGRs) such as:

Table 1: Table Title: Effects of PGPR and Plant Growth Regulators in Combination with Chitosan

PGPR	Effect in combination with chitosan
Gibberellic acid (GA ₃)	Improved stem elongation and fruit development
Salicylic acid (SA)	Enhanced disease resistance and stress tolerance
Jasmonic acid (JA)	Synergistic activation of defense pathways
Brassinosteroids	Improved photosynthesis and stress tolerance

Economic feasibility and adoption challenges

Cost-benefit analysis

Although agricultural inputs containing chitosan require a greater initial investment than traditional agrochemicals, they offer compelling long-term financial advantages. Field research indicates that utilizing chitosan can boost harvests by 15% to 30% and simultaneously decrease the need for standard fertilizers by 20% to 40%, ultimately widening profit margins. Depending on the specific crop and application technique, fertilizers enriched with chitosan deliver an estimated return on investment (ROI) between 1.5 and 3.0.

Barriers to adoption

Despite the demonstrated benefits, several barriers limit farmer adoption:

- High production costs:** Current production costs (\$15-25/kg) are significantly higher than synthetic fertilizers (\$0.5-2/kg)
- Limited availability:** Lack of established supply chains in many agricultural regions
- Knowledge gaps:** Farmers require training on optimal application methods and timing
- Quality inconsistency:** Variable product quality from different manufacturers
- Regulatory uncertainty:** Unclear registration requirements for biopolymer-based products in many countries

Safety and regulatory aspects

Comprehensive toxicology evaluations demonstrate that chitosan poses no toxicity threat to mammals, showcasing an oral LD₅₀ exceeding 5,000 mg/kg in rat models (EFSA, 2023). The United States Food and Drug Administration (FDA) designates it as Generally Recognized as Safe (GRAS) across multiple uses. Nevertheless, because it is primarily sourced from crustaceans, manufacturers must implement proper labeling to alert end-users of potential allergic reactions.

Challenges and future prospects

While chitosan holds vast promise for eco-friendly farming, several hurdles impede its universal acceptance. Fluctuations in its source materials, extraction protocols, molecular weight, and

deacetylation levels frequently cause unreliable field performance and quality (Rinaudo, 2006) ^[51]. Furthermore, steep manufacturing expenses and restricted scalability make it difficult for smallholder farmers to access these solutions (Katiyar *et al.*, 2015) ^[31]. The absence of clear regulatory guidelines in various nations, coupled with a pressing need for extensive field trials across varied climates to refine real-world applications, further complicates its rollout.

Moving forward, scientific investigations must prioritize the creation of economical extraction techniques, advanced nano-formulations, and targeted delivery mechanisms, while blending chitosan inputs with digital and precision agriculture frameworks (Iqbal, 2024) ^[29]. Leveraging omics technologies such as metabolomics, proteomics, and genomics alongside combinations of chitosan, nanomaterials, humic acids, and helpful microbes will likely unlock a more profound understanding of how this biopolymer influences plant biology at a molecular level (Katiyar *et al.*, 2015; Agbodjato *et al.*, 2026) ^[31].

Conclusion

Chitosan stands out as a versatile biopolymer uniquely positioned to advance sustainable farming practices. Thanks to its natural biodegradability, coupled with robust biostimulatory, metal-chelating, and antimicrobial traits, it serves as a highly viable substitute for traditional synthetic chemicals (Rinaudo, 2006; Katiyar *et al.*, 2015) ^[31, 51]. Applications ranging from surface coatings and hydrogels to nanoparticles and enhanced fertilizers actively elevate crop yields, soil vitality, stress resilience, and post-harvest longevity while optimizing nutrient uptake (Muñoz *et al.*, 2018; DeGroot & Neufeld, 2001) ^[10, 42]. The agricultural footprint of chitosan continues to grow, fueled by breakthroughs in circular bioeconomy frameworks, intelligent delivery methods, and nanotechnology (Iqbal, 2024; Sustainable Chemistry One World, 2026) ^[29, 57]. Even though obstacles like high costs, mass production scaling, and product standardization persist, ongoing innovation will undoubtedly solidify its practical value over time (Yan *et al.*, 2023) ^[63]. Merging chitosan technology with biorefinery models, precision farming, and microbial treatments paves the way for farming systems that are both ecologically sound and financially

profitable (Agbodjato *et al.*, 2026). Ultimately, adopting chitosan-driven agricultural methods marks a critical leap toward securing the global food supply while deliberately curbing environmental degradation.

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