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Chitosan as a sustainable biomaterial: A review of sources, key properties, applications and the emergence of nano-chitosan

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Abstract

Chitosan is a natural biopolymer obtained by the partial deacetylation of chitin and has attracted considerable attention because of its biodegradability, biocompatibility, and versatile biological activities. The objective of this review was to provide an integrated overview of chitosan, focusing on its major sources, key physicochemical properties, agricultural applications, and the emerging role of nanochitosan. The review summarized and analyzed scientific publications from 2013 to 2025 with respect to chitosan and nanochitosan. The review result of available literature showed that chitosan can be produced from crustaceans, insects, and fungi, with source-dependent differences in purity, production feasibility, and functional performance. Among its physicochemical characteristics, molecular weight and degree of deacetylation are two major determinants of solubility, reactivity, biological activity, and application suitability. In agriculture, chitosan has been widely investigated for antimicrobial activity, seed coating, plant growth promotion, and stress mitigation. However, conventional chitosan still faces practical limitations related to water solubility, formulation stability, and variability in field performance. Nanochitosan has therefore emerged as a promising functional upgrade because its nanoscale formulation can improve dispersion, bioavailability, controlled delivery, and interactions with plant and microbial systems. Overall, chitosan and nanochitosan show strong potential as sustainable materials for modern agriculture, although further work is still needed to standardize production, optimize formulation properties, and strengthen field-scale validation.

Keywords: Agriculture; Antimicrobial; Chitosan; Deacetylation; Fungal chitosan; Molecular weight; Nanochitosan

1. Introduction

The transition toward more sustainable agricultural systems has increased interest in biodegradable and renewable biomaterials that can reduce dependence on synthetic agrochemicals. Among these materials, chitosan has emerged as one of the most promising candidates because of its biocompatibility, biodegradability, low toxicity, and broad functional versatility. Produced through the partial deacetylation of chitin, chitosan has been widely investigated in several fields, including biomedicine, food, environmental applications, and agriculture [1, 2].

In agriculture, chitosan has attracted considerable attention because of its antimicrobial properties, ability to stimulate plant defense responses, and potential to support seed treatment, crop growth, and stress tolerance [3]. Previous

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studies have shown that chitosan can inhibit a wide range of plant pathogens, including fungal genera such as Fusarium, which are responsible for major diseases in many economically important crops [4]. In addition, chitosan-based systems have been explored as sustainable alternatives for reducing reliance on conventional pesticides and improving crop performance under both biotic and abiotic stress conditions [2].

However, the efficiency of the traditional chitosan products has some limitations, especially regarding their solubility, stability, and ability to control the release of active ingredients. Therefore, recent research has been directed towards the development of nanochitosan to improve its efficiency, thus improving its antimicrobial efficacy and its applications in agriculture [5]. Furthermore, the exploitation of new chitosan sources, such as those from fungi or insects, is also attracting attention towards sustainable development and the utilization of available resources.

This review examines chitosan from an application-oriented agricultural perspective by linking three major dimensions: source, physicochemical properties, and functional performance, particularly how source-dependent characteristics and key parameters such as molecular weight and degree of deacetylation influence the behavior of chitosan in plant protection, seed treatment, and growth stimulation. The review also highlights the main practical limitations of conventional chitosan under field conditions and explains why nanochitosan is increasingly being explored as a functional upgrade. By integrating these aspects, this review aims to clarify current knowledge, identify key limitations, and outline future directions for the development of more effective and sustainable chitosan-based systems in agriculture.

2. Chitosan fundamentals

Chitin is a naturally occurring polysaccharide. It is recognized as the second most abundant biopolymer, after cellulose. It is also recognized as having a considerable occurrence in the biosphere [6]. In terms of structure, chitin is recognized as a polysaccharide constructed from units of β-(1→4)-linked N-acetyl-D-glucosamine. It is recognized as a major structural component of the exoskeleton of marine crustaceans, including shrimp and crab, as well as insects, and the cell walls of fungi [7]. In nature, chitin occurs as crystalline microfibers of high order. It occurs in three crystalline forms: α-chitin, β-chitin, and γ-chitin. α-chitin is the most common, found in arthropods and crustaceans. In contrast, β-chitin, which is less mechanically strong and harder than α-chitin, is more elastic and is found in diatom spines, ink pens, and pogonophora tubes. γ-chitin, the least common and least studied form, is found in fungi, yeast, and insect cocoons [8, 9].

Chitosan is generally regarded as the deacetylated derivative of chitin and is mainly composed of D-glucosamine and N-acetyl-D-glucosamine units linked by β-(1→4) glycosidic bonds. In practical terms, the distinction between chitin and chitosan is often associated with a sufficiently high degree of deacetylation that confers acid solubility and polycationic behavior under mildly acidic conditions [10]. Compared with chitin, chitosan contains a higher proportion of free amino groups, which contributes to its greater reactivity and broader derivatization potential. The presence of free amino groups enables the production of a wide range of chitosan derivatives. The polymer is defined as chitosan if the degree of acetylation of the repeating units is less than 50%. Chitosan is defined as a non-toxic, semi-crystalline, hydrophilic biopolymer with characteristics associated with green materials, which include adjustable molecular weight, degree of deacetylation, and a high complexing ability [2].

Despite having favorable properties, chitosan is insoluble in water and other organic solvents but shows appreciable solubility in acidic media due to the protonation of amino groups at pH ≤ 6.0, which is responsible for the polycationic nature of chitosan [11, 12]. Its low mechanical properties also play an important role in the processing and application of chitosan in different fields.

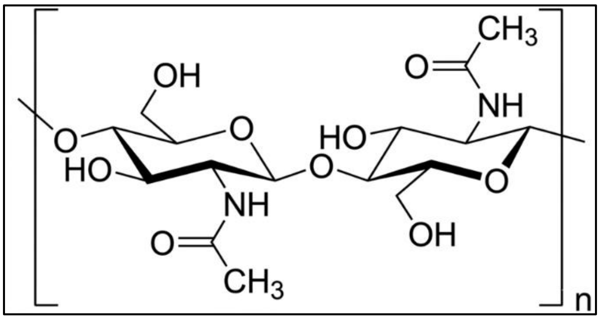

Figure 1 Structure of chitin [13]

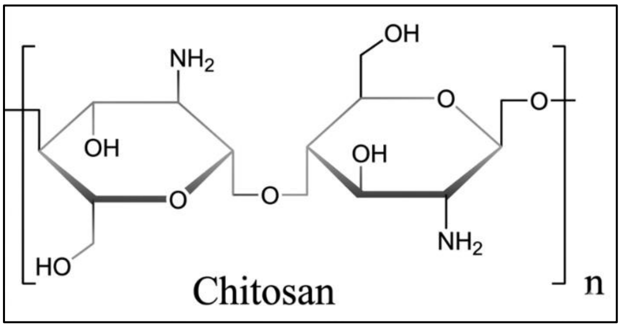

Figure 2 Structure of chitosan [1]

2.1. Degree of deacetylation (DD)

The degree of deacetylation (DD) is a major parameter that influences the structural composition and functionality of chitosan. It refers to the deacetylated units of D-glucosamine residues in the chitosan polymer chain. This parameter is important in the determination of the physicochemical and biological properties of chitosan [14]. Generally, chitosan is soluble under practical conditions when the DD is above a minimum of 50-60%. This is important for the application of chitosan in different fields [7, 15]. In this regard, the DD of chitosan is quantified using different spectroscopic methods. This includes Fourier transform infrared spectroscopy, UV spectroscopy, potentiometric titration, nuclear magnetic resonance spectroscopy, and many more [7]. Moreover, the biological source used for the production of chitosan and the method used for the extraction of chitosan have a significant impact on the DD. In general, a higher degree of deacetylation increases the density of free amino groups and may enhance the reactivity, solubility in acidic media, and biological interactions of chitosan, although its functional performance also depends on molecular weight, formulation, and application conditions.

2.2. Molecular weight (MW)

Molecular weight (MW) is one of the basic and crucial characteristics of chitosan, which largely defines the physical and biological properties as well as application areas of this compound [2, 15]. The value of MW corresponds to the amount of repeat units present in the chitosan chain and, therefore, influences its solubility, viscosity, ability to swell, and biological activity. Based on MW, chitosan is usually classified: oligochitosan (<50 kDa), low molecular weight chitosan (<150 kDa), medium molecular weight chitosan (150–700 kDa), and high molecular weight chitosan (>700 kDa) [16]. This classification is useful because molecular weight strongly influences viscosity, solubility, diffusion, film-forming behavior, and biological activity. Differences in MW lead to distinct differences in application: low MW chitosan has high solubility, readily interacts with biological systems, and often exhibits stronger antimicrobial and antifungal activity, especially in agricultural and environmental applications [2, 13], while high MW chitosan with high deacetylation is more suitable for applications requiring mechanical strength and film-forming ability such as tissue engineering, drug delivery systems, and food packaging [17]. In addition to this, MW will influence the properties of chitosan particles, including size, ability to form clusters, and surface behavior, hence affecting the effectiveness of its application [18]. Regarding the identification of MW, there are different ways of achieving this, which include light scattering, gel permeation chromatography, and viscometry, among others, out of which viscometry remains the most widely used, though not the most accurate [7]. Overall, molecular weight is one of the major parameters governing the functional performance of chitosan across different applications.

3. Sources for chitosan

In general, chitosan is produced from chitin by a series of deacetylation reactions. Chitin is a naturally occurring substance in sea creatures, insects, and fungi. In order for a chemical to be classified as a derivative of chitosan, it must be deacetylated to a degree higher than 60% [19]. Among these natural sources of chitosan, crustacean materials are still the most prominent; however, insects and fungi are also increasingly becoming a viable option.

3.1. Crustacean-derived chitosan

Crustacean shells, especially from shrimp, crab, and lobster, represent the most commonly used feedstock for the production of chitosan. This is because they are readily available in large quantities as waste from the seafood processing industries. In general, the crustacean shells have a chitin content of 20-30%, along with considerable amounts of calcium carbonate (30-50%) and protein (30-40%) [7]. In the world market, the processing of shellfish products results in waste of up to 1.44 million metric tons per annum, which is cost-effective [8]. The process of chitosan synthesis from the crustacean shells involves a series of chemical reactions, including deproteinization, demineralization, decolorization, and deacetylation [19]. Even though the process of chitosan synthesis from crustacean shells is well established, it demands a substantial quantity of chemical reagents and energy, especially in the form of high temperatures and alkali solutions [20]. However, there are some limitations associated with the use of crustacean-derived chitosan. These limitations include the seasonal fluctuations and geographic factors associated with marine resources. In addition, the method of obtaining chitosan from crustaceans results in the formation of effluent, which is said to contain impurities such as metals and allergens. Besides, it is difficult to obtain chitosan with specific physicochemical properties, e.g., molecular weight [20].

3.2. Insect-derived chitosan

Insects have been identified as a new source of chitosan production, and this is attributed to the biodiversity of insects, which makes them a sustainable source of chitosan, as it is noted that 95% of animal species are insects. The chitin concentration of insects is between 7 and 20%. The yield of chitosan from insects ranges from 67% to 72%, which is close to that obtained from crustaceans [7]. The use of insects as a source for chitosan production offers a number of advantages, as the amount of inorganic matter found in insect cuticles is less, which makes the process of demineralization simpler. Moreover, insect farming can be linked to waste management, which can provide a more efficient approach to utilizing waste. The physicochemical properties, like the level of deacetylation and the molecular weight, have also been reported to be similar to those produced from crustaceans [19]. The development of the use of insects as a feedstock for chitosan is still in the early stages. Most of the work carried out so far has been on a small scale. Some of the challenges that have been identified with the development of the use of chitosan include the challenges of standardizing the process, scaling the process, and ensuring quality. In addition, the quality of the feed used may also have a bearing on the quality of the chitosan produced.

3.3. Fungal-derived chitosan

Fungal chitosan, derived from fungi, has proven to be a very promising and environmentally friendly substitute for the traditional sources of chitosan. This is especially true when the concept of green chemistry is considered. Chitin and chitosan have a crucial position in the cell walls of the following classes of fungi: *Ascomycetes*, *Basidiomycetes*, and *Zygomycetes*. In terms of percentage, the chitin-chitosan content in the cell walls of the fungus may vary from 2 to 65%. The well-known fungi *Aspergillus niger*, *Mucor rouxii*, and *Rhizopus oryzae* have already shown their potential in terms of chitin content and easy cultivation [7]. One of the most significant advantages of fungal chitosan is that it can be produced via controlled fermentation throughout the year, without the seasonal and geographical limitations associated with crustacean-derived materials. Additionally, fungal chitosan generally contains lower levels of inorganic material, which may reduce the need for demineralization and decrease chemical consumption during extraction [19]. Mushroom chitosan does not contain heavy metals or allergenic proteins present in crustacean chitosan. In comparison to chitosan derived from crustaceans, chitosan derived from fungi tends to have a lower molecular weight, a lower polydispersity index, and a uniform particle size distribution, which may improve its biological activities, especially antimicrobial and plant defense-inducing activities [21]. While many benefits have been mentioned above, there are still some issues with large-scale productions. Specifically, it is stated that the capability of producing biomass within fungi is less than that from crustacean wastes; moreover, the extraction process has not been optimized for mass-scale production [7]. Besides, the production of chitosan from fungi depends on the type of fungus used, the system of cultivation, as well as the media composition; all those factors affect both the efficiency of the process itself and the characteristics of the end-product obtained [22]. Nonetheless, through the optimization process of fermentation techniques, one may enhance the significance of the green material of chitosan produced from fungi, namely its functionality to be used in agriculture and in controlling diseases of plants. From an agricultural perspective, fungal chitosan is particularly attractive because fermentation-based production may offer better control over biomass generation and material consistency than waste-derived sources. Its lower inorganic impurity burden, reduced allergen risk, and potentially more uniform physicochemical properties may support the development of more reproducible agricultural formulations. Although large-scale production and process optimization remain major challenges, fungal chitosan represents one of the most promising directions for sustainable and application-specific chitosan production.

Table 1 Comparative advantages and disadvantages of chitosan sources

Source	Advantages	Disadvantages
Crustaceans	Plentiful and cheap natural feedstock from seafood waste, well-established industrial processes, and good chitin yield [7, 8].	High chemical and energy consumption during extraction [20]; environmental pollution from effluents; seasonal and location-dependent supply; risk of heavy metals and allergenic proteins.
Insects	Renewable resource with high biodiversity [7]; less mineral content leading to easier extraction [23]; comparable DD and MW to crustaceans [19].	Limited to laboratory-scale research; no standardized processes available; varies depending on species and rearing conditions.
Fungi	Year-round production via fermentation [20]; low chemical usage and eco-friendly extraction [19]; free from heavy metals and allergens; tunable MW and DD; high purity and uniformity [1].	Lower biomass yields; higher production costs; extraction & scale-up processes not yet fully optimized [7]

4. Agricultural applications of conventional chitosan

In agriculture, the value of chitosan lies not only in its biopolymeric nature but also in the way its physicochemical properties influence biological performance. Its agricultural functions are strongly affected by molecular weight, degree of deacetylation, formulation, dosage, and method of application. Based on the available literature, the main agricultural applications of conventional chitosan can be broadly grouped into antimicrobial protection, seed treatment, and biostimulant activity.

4.1. Antimicrobial activity

Chitosan has shown inhibitory activity against a broad range of plant pathogens, including fungal genera such as *Fusarium*, *Alternaria*, and *Rhizopus*, as well as bacterial genera such as *Pseudomonas* and *Xanthomonas* [10]. Its antimicrobial action is mainly attributed to its polycationic character under acidic conditions, which enables protonated amino groups to interact with negatively charged microbial cell surfaces. This interaction can disrupt membrane integrity, alter permeability, and lead to leakage of intracellular components. In some cases, low-molecular-weight or nanoscale chitosan may also penetrate microbial cells more effectively and interfere with intracellular processes such as protein synthesis and nucleic acid function [2].

However, the antimicrobial efficiency of chitosan is not constant across studies. Reported performance depends on several factors, including molecular weight, degree of deacetylation, concentration, pH, formulation type, and the target microorganism. In this context, nanochitosan and metal-associated chitosan systems, such as Zn-, Cu-, or Ag-containing formulations, have often shown enhanced antimicrobial performance compared with conventional chitosan, especially in the control of soil-borne and wilt-associated plant diseases [8, 15]. In addition to direct antimicrobial effects, chitosan can also act indirectly by stimulating plant defense responses, including the accumulation of phytoalexins, lignin, callose, and antioxidant-related protective systems, thereby improving resistance against pathogen attack [7].

4.2. Seed coating

Seed coating is one of the most widely investigated agricultural uses of chitosan. As a coating material, chitosan can form a protective layer around the seed surface, helping reduce exposure to pathogenic microorganisms and environmental stress during germination [1]. In many studies, chitosan-treated seeds have shown improved germination performance, better early seedling vigor, and enhanced resistance to biological stress. These benefits are often associated with the elicitor-like behavior of chitosan, which can stimulate defense-related gene expression, regulate phytohormonal responses, and promote antioxidant activity during early seedling development [7].

Chitosan treatment has also been associated with increased phenolic content and activation of antioxidant enzyme systems, which may strengthen seedling tolerance to infection during germination, including infection by fungal pathogens such as *Fusarium graminearum* [1]. Nevertheless, the effects of chitosan-based seed coating are not always consistent. Reported outcomes vary with crop species, developmental stage, molecular weight, degree of deacetylation, formulation characteristics, and application concentration [2]. Therefore, although chitosan is a promising eco-friendly seed treatment material, its practical efficiency still depends on careful optimization for each crop and application context.

4.3. Biostimulant

Chitosan is also widely recognized as a potential biostimulant because it can promote plant growth and support physiological adaptation to stress. Its biostimulant effects have been linked to improved germination, root development, biomass accumulation, nutrient uptake, and activation of defense- and hormone-related pathways. Low-molecular-weight chitosan is often considered more readily soluble and more biologically interactive, which may favor rapid absorption and stronger elicitor-like responses in plants [2, 7].

By contrast, medium- and high-molecular-weight chitosan fractions may exert stronger surface-level effects, including film formation, improved moisture retention, and support for resistance to abiotic stresses such as salinity and water limitation. These responses are often associated with increased phenolic accumulation and enhanced antioxidant enzyme activity [2] Chitosan has also been reported to contribute to nutrient absorption and metabolic activity, thereby supporting crop productivity under suitable conditions [10]. However, its biostimulant performance is not universally predictable. Responses vary with plant species, developmental stage, molecular weight, dosage, and method of application, and inappropriate use may lead to reduced effectiveness or even adverse effects on crop growth. Overall, the available literature supports the promise of chitosan as a sustainable agricultural biostimulant, but more standardized formulations and application strategies are still needed for reliable field performance.

5. Limitations of conventional chitosan

Despite its strong potential in sustainable agriculture, conventional chitosan still faces several practical limitations under field conditions. One of the main constraints is its poor solubility in water, as chitosan is generally soluble only in acidic media due to protonation of its amino groups. This property can complicate formulation, storage, and application under neutral environmental conditions [1, 15]. In addition, conventional chitosan often shows variability in performance because its biological activity is strongly influenced by molecular weight, degree of deacetylation, concentration, pH, and formulation characteristics [2, 14]. Its relatively high molecular weight, limited dispersion, and tendency to aggregate may also reduce penetration efficiency and biological interaction in some applications. Another important limitation is the limited stability and controlled-release capacity of conventional chitosan systems, which may reduce persistence and effectiveness on plant surfaces or in soil [7]. These challenges have encouraged the development of nanochitosan and other advanced formulations to improve solubility, dispersion, delivery efficiency, and consistency in agricultural use [8, 15].

6. The emergence of nanochitosan

While conventional chitosan holds significant promise as a sustainable biopolymer, its practical deployment in modern agriculture is frequently hindered by fundamental limitations, particularly its poor aqueous solubility at neutral pH and restricted systemic mobility within complex plant tissues. To address these macroscopic constraints, research focus has shifted toward nano-engineering strategies. The following sections explore the transformative role of nanochitosan, examining its emergence and superior functional features as a smart delivery system for next-generation agricultural applications.

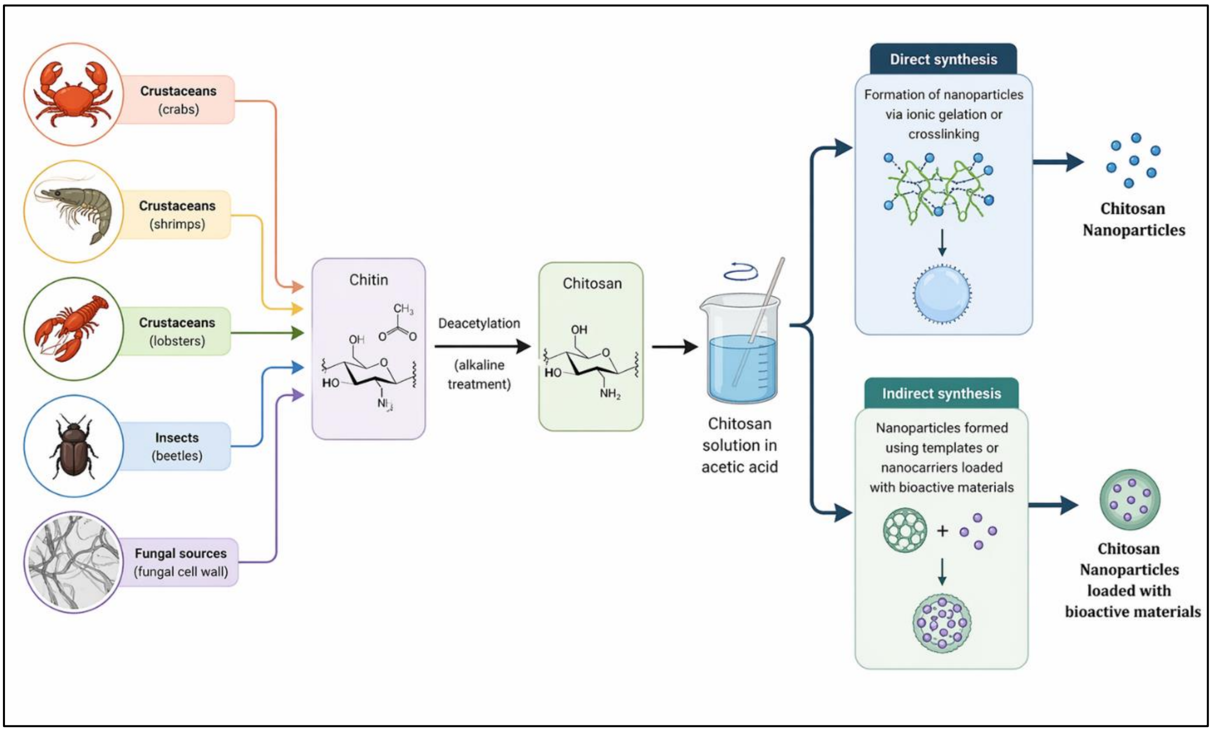

Figure 3 Biological synthesis and formulation of nanochitosan

6.1. Emergence and utilization of nanochitosan

The agricultural sector is in a state of continuous evolution, perpetually seeking innovative, eco-friendly materials to replace synthetic chemicals and promote sustainable farming practices. In this historical transition, bulk biopolymers initially gained traction; however, their macroscopic limitations rapidly necessitated a shift toward nanotechnology. Nanochitosan emerged as a transformative and highly efficient solution, bridging the critical gap between natural biopolymers and advanced nanoscale engineering [24]. The transition from bulk chitosan to its nano-formulation was driven primarily by the need to overcome fundamental constraints related to solubility, reactivity, and application efficiency in complex agricultural environments. By reducing the polymer to the nanoscale, researchers unlocked a new realm of physicochemical properties that dramatically amplified its biological efficacy [25].

Globally, the utilization of nanochitosan has witnessed an exponential increase, moving swiftly from a laboratory curiosity to broad field-level applications. This emergence is heavily intertwined with the growing awareness of sustainable agricultural practices and the urgent need to ensure global food security without degrading environmental resources. Nanochitosan is now being extensively utilized across a multitude of agronomic domains, serving simultaneously as a potent biostimulant, a highly effective antimicrobial agent, and a foundational material for smart agricultural delivery systems [26]. Its versatility allows it to be integrated into seed coatings, foliar sprays, and soil amendments, providing farmers with a multifaceted tool to enhance crop resilience.

Furthermore, the rapid emergence of this nanomaterial is supported by its exceptional safety profile and biocompatibility. As the global demand for natural and organic agricultural inputs surges, nanochitosan has been embraced as a premier option that guarantees high crop yields while maintaining ecological harmony. The robust antioxidant and antimicrobial properties inherent in the nanoscale chitosan not only protect crops during their growth phases but also extend the post-harvest shelf life of agricultural commodities, showcasing a full-cycle utilization loop [27]. Consequently, nanochitosan is no longer viewed merely as an alternative biomaterial but rather as a central pillar in the next generation of high-tech, sustainable agriculture.

6.2. Functional features of nanochitosan

Nanochitosan is not merely a downsized form of its parent biopolymer; rather, it is an advanced nanoscale formulation that exhibits a fundamentally enhanced functional repertoire. The most defining functional feature of nanochitosan is its extraordinarily high specific surface area-to-volume ratio, which completely alters its dispersibility, surface reactivity, and interfacial interactions within biological systems [26]. At the nanoscale, the physical constraints that typically limit bulk chitosan are eliminated, allowing the nanoparticles to maintain superior colloidal stability and uniform dispersion in various aqueous agricultural formulations. This stable colloidal behavior is crucial for ensuring that the active properties of the material are delivered consistently and homogeneously across treated crops [28].

At the molecular and functional level, nanochitosan intrinsically retains the characteristic polycationic nature of bulk chitosan, but it vastly improves the spatial accessibility of its reactive amino ($-NH_2$) and hydroxyl (-OH) functional groups [29]. When suspended in slightly acidic to neutral environments, these densely packed, protonated amino groups create a strong positive surface charge (high zeta potential). This feature supports exceptionally strong electrostatic interactions with the negatively charged components of plant cell walls and microbial cell envelopes, serving as the primary functional driver for its antimicrobial and elicitor-like activities. The nanoscale format allows these functional groups to bind more tightly and specifically to biological targets than bulk polymers ever could.

The practical value of these functional features is strongly supported by recent empirical evidence in crop science. For instance, the application of chitosan nanoparticles on specific crops such as lettuce (*Lactuca sativa* L.) and various solanaceous plants has demonstrated remarkable functional outcomes. The nanoparticles act as potent biostimulants that directly enhance physiological traits, elevate chlorophyll synthesis, and increase the accumulation of vital secondary metabolites like phenolics and flavonoids [30]. By serving concurrently as an active biological elicitor and a highly reactive surface interface, the functional features of nanochitosan provide an all-encompassing platform that actively modulates plant growth pathways while structurally protecting the plant from external biotic pressures.

6.3. Advantages over conventional chitosan

When directly compared to conventional bulk chitosan, nano-engineered chitosan presents a multitude of profound agronomic and physicochemical advantages that significantly elevate its application value. The most prominent advantage lies in overcoming the severe solubility barriers that have historically plagued conventional chitosan. Bulk chitosan exhibits notoriously poor solubility at neutral pH levels, requiring acidic solvents that can occasionally induce unwanted phytotoxic stress when applied to delicate crops. In stark contrast, nanochitosan demonstrates superior dispersibility and stability across a much broader pH spectrum, allowing it to be easily integrated into standard, water-based agricultural irrigation and spraying systems without the need for harsh chemical solvents [31].

Beyond solubility, the physical dimensions of nanochitosan confer an unparalleled advantage in terms of biological penetration and systemic mobility. Conventional chitosan, due to its large macromolecular size, primarily remains on the external surfaces of plant tissues, forming a superficial film. Conversely, nanochitosan particles (typically ranging from 20 to 100 nanometers) are small enough to effectively bypass major morphological barriers. They can easily permeate through cuticular pores, stomatal openings, and the intricate matrix of root epidermal cells [28]. This enhanced internalization ensures that the active biopolymer is transported systemically through the plant's vascular tissues, delivering biological benefits directly to intracellular targets rather than being washed away by environmental factors.

Furthermore, the exceptional surface reactivity of nanochitosan translates into a massive advantage regarding application efficiency and dosage reduction. Because a significantly larger proportion of the polymer's active functional groups are exposed and available for interaction, nanochitosan achieves superior antimicrobial and biostimulant effects at a fraction of the concentration required for conventional chitosan [29]. This dramatic reduction in required dosage not only makes agricultural operations more economically efficient but also prevents the excessive accumulation of residues on crop surfaces. Additionally, the nanoscale structure offers extraordinary formulation compatibility, seamlessly blending with other organic agrochemicals without precipitating, a feat that conventional chitosan struggles to achieve consistently [2].

6.4. Mechanisms of action at the nanoscale in plant systems

The efficacy of nanochitosan in plant systems is governed by highly sophisticated, nanoscale mechanisms of action that operate at both the cellular and molecular levels. The initial mechanism involves the aggressive electrostatic binding of the positively charged chitosan nanoparticles to the negatively charged domains of the plant cell wall, particularly the pectin matrix and plasma membrane. This interaction rapidly alters membrane permeability, facilitating the efficient internalization of the nanoparticles via endocytosis-like pathways or direct pore penetration. Once internalized, nanochitosan functions as an exceptionally potent secondary messenger, cascading signals through the plant's intracellular communication networks to trigger profound physiological and biochemical adaptations [27].

A primary target of these mechanisms is the enhancement of the plant's photosynthetic machinery. Nanochitosan directly upregulates the synthesis of vital photosynthetic pigments, significantly elevating the concentration of chlorophyll a, chlorophyll b, and protective carotenoids. More importantly, it actively safeguards the ultrastructure of chloroplasts from oxidative degradation and optimizes the efficiency of key photosynthetic enzymes, such as RuBisCO, ensuring maximum carbon assimilation even under sub-optimal growing conditions [32]. This targeted action on the photosystems ensures that the plant has a robust energy surplus to fuel accelerated growth, node development, and robust biomass accumulation.

Concurrently, nanochitosan operates through a powerful elicitor mechanism that modulates the plant's endogenous antioxidant defense systems. The introduction of these nanoparticles stimulates the rapid, systemic expression of genes responsible for producing crucial antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) [32]. These enzymes work synergistically to scavenge reactive oxygen species (ROS) and prevent lipid peroxidation, maintaining absolute cellular integrity. Additionally, the nanoparticles trigger the accumulation of potent intracellular osmoprotectants such as proline, soluble sugars, and specialized alkaloids [33]. Through these intricate biochemical pathways, nanochitosan actively reprograms the plant's metabolic baseline, transforming it into a highly resilient and productive biological system.

6.5. Nanochitosan as a smart delivery system for agrochemicals

In the realm of modern precision agriculture, nanochitosan has firmly established itself as an elite, "smart" delivery system for a wide array of agrochemicals, including synthetic fertilizers, essential micronutrients, and powerful pesticides. Conventional agricultural practices suffer from severe inefficiencies; a vast majority of applied agrochemicals are rapidly lost to the environment through soil leaching, atmospheric volatilization, or premature microbial degradation. Nanochitosan specifically addresses this systemic inefficiency by acting as a highly protective, nanoscopic capsule. Through advanced encapsulation techniques, sensitive active ingredients are securely entrapped within the biopolymer matrix, shielding them from harsh environmental degradation and ensuring their absolute molecular integrity until they reach the intended biological target [34, 35].

The defining characteristic of this smart delivery system is its unparalleled capacity for controlled and stimuli-responsive release. Unlike traditional fertilizers that flood the soil with nutrients instantly, nanochitosan matrices are meticulously engineered to release their cargo at a calculated, sustained rate. The release kinetics are governed by the gradual swelling and enzymatic biodegradation of the chitosan shell. Furthermore, this delivery mechanism is uniquely "smart" because it can be tailored to respond directly to specific environmental stimuli, such as subtle shifts in soil pH, moisture fluctuations, or the presence of specific enzymes secreted by plant root exudates [36]. This ensures that agrochemicals are delivered in perfect synchrony with the plant's developmental demands, radically maximizing nutrient use efficiency.

Moreover, utilizing nanochitosan as a delivery platform offers a synergistic, dual-action benefit that synthetic carriers cannot replicate. While the nanocarrier efficiently transports and releases the encapsulated pesticide or fertilizer, the chitosan shell itself simultaneously imparts its inherent antimicrobial and biostimulant properties to the surrounding soil and plant tissues [37]. This means that as the nanoparticle degrades, it continuously nourishes the crop and suppresses soil-borne pathogens. The utilization of such intelligent, eco-friendly nano-insecticides and nano-fertilizers represents a monumental leap forward, enabling high-performance crop management while drastically minimizing the overall volume of chemicals introduced into the agricultural ecosystem [38].

6.6. Production and formulation of nanochitosan

The successful production of nanochitosan relies heavily on highly precise, bottom-up formulation strategies that meticulously construct nanoparticles from molecular chitosan precursors. Among the diverse array of available synthetic routes which include polyelectrolyte complexation, microemulsion, nanoprecipitation, and spray-drying ionotropic gelation remains the absolute gold standard for agricultural applications [5]. This method is celebrated for its remarkable simplicity, high efficiency, and uniquely mild operating conditions. The process fundamentally relies on the spontaneous electrostatic cross-linking between the positively charged amino groups of the chitosan polymer chain and negatively charged multivalent polyanions, most notably sodium tripolyphosphate (TPP), occurring entirely within an aqueous, solvent-free environment [39].

The true sophistication of nanochitosan production lies in the precise manipulation of formulation parameters to dictate the final physicochemical profile of the nanoparticles. Variables such as the molecular weight of the parent chitosan, the exact degree of deacetylation, the pH of the surrounding solution, and the highly specific chitosan-to-TPP stoichiometric ratio must be rigorously calibrated. These parameters directly govern the critical attributes of the nanoparticles, including their mean hydrodynamic diameter, polydispersity index (PDI), and the density of their positive surface charge (zeta potential) [40]. By fine-tuning these specific variables, researchers can engineer nanoparticles with tailored porosities and structural integrities, perfectly customized for specific agricultural tasks.

Furthermore, these production techniques are highly adaptable, allowing for the creation of sophisticated, multi-component nanocomposites. During the ionotropic gelation or spray-drying phases, secondary active ingredients such as liquid essential oils, trace mineral salts, or complex phytohormones can be seamlessly integrated into the polymer matrix, achieving exceptional encapsulation efficiencies [41]. Modern advancements in emulsification-based systems also allow for the precise tuning of the nanoparticle's hydrophobic and hydrophilic balance, ensuring maximum stability when applied as foliar sprays. Ultimately, the meticulous science of nanochitosan formulation ensures that the material transcends basic nanoparticle fabrication, evolving into a highly engineered, purpose-built agronomic platform.

6.7. Commercialization perspectives

The commercialization landscape for nanochitosan in the agricultural sector is experiencing unprecedented, exponential growth, driven by an overwhelming global demand for high-efficiency, sustainable farming solutions. Recent market analyses reveal a dramatic expansion in production capacity; in 2024, the global production of chitosan reached an astounding 38,000 metric tons, with agriculture and agrochemical sectors directly consuming over 5,400 metric tons [42]. This massive market penetration is heavily fueled by the compelling return on investment that nanochitosan products offer to commercial farming operations. Extensive agricultural trials conducted globally have consistently demonstrated that crops treated with advanced chitosan-based nano-formulations exhibit average yield increases of over 13%, alongside vastly improved product quality and extended shelf life [27].

From an industrial scale-up perspective, the transition from laboratory batch synthesis to large-scale, continuous commercial manufacturing has been remarkably successful. Leading biotechnology firms and major agrochemical corporations have heavily invested in optimizing bottom-up synthesis methods, successfully engineering massive production pipelines that maintain strict quality control, ensuring consistent nanoparticle size and morphological homogeneity across multi-ton batches [24]. The economic viability of these commercial operations is further bolstered by the utilization of abundant, renewable feedstocks, such as crustacean waste and fungal biomass, which perfectly aligns with profitable, circular bioeconomy models, drastically lowering raw material costs.

Moreover, the commercialization of nanochitosan is accelerating due to a highly favorable global reception. As the modern agricultural industry aggressively pivots towards natural and organic ingredients, nanochitosan has emerged as a premium, highly sought-after commodity. Food manufacturers, large-scale commercial farms, and greenhouse operators are rapidly integrating these nano-biostimulants into their standard operational protocols to guarantee both the safety and the nutritional superiority of their products [31]. This enthusiastic market adoption, coupled with continuous technological advancements in formulation stability, firmly positions nanochitosan as one of the most lucrative and rapidly expanding segments within the global agricultural biotechnology market.

6.8. Nanochitosan research and applications in Vietnam

In Vietnam, a country heavily reliant on intensive agriculture and aquaculture, nanochitosan is rapidly transforming the landscape of high-tech, sustainable farming. The unique geographical and climatic challenges of Vietnam, particularly the increasing salinity and climate volatility in critical agricultural hubs like the Mekong Delta, have driven domestic researchers to aggressively adopt nanotechnology. Prominent national institutions are leading the charge in this scientific revolution. For instance, pioneering research spearheaded by the Vietnam Academy of Science and Technology (VAST) has successfully developed highly advanced nanochitosan production protocols. These cutting-edge formulations have been actively applied in field trials to stimulate the growth and development of rice crops, yielding exceptionally positive results in practical farming environments and proving their immense commercial viability [43].

Beyond traditional crop farming, the application of nanochitosan has expanded deeply into Vietnam's massive aquaculture sector. Recognizing the urgent need to transition away from the overuse of synthetic antibiotics in intensive shrimp and fish farming, Vietnamese biotech enterprises and research institutes have successfully deployed nanochitosan as a powerful, natural immunostimulant. These nano-sized particles effectively enhance the innate immunity of aquatic species, vastly improving survival rates and production yields in the Mekong Delta, which accounts for the vast majority of the nation's shrimp output [44]. This integrated approach perfectly aligns with Vietnam's strategic goal of producing clean, export-grade agricultural and aquatic products.

The momentum of nanochitosan research in Vietnam is further accelerated by strong synergistic collaborations between academic institutions, governmental bodies, and the private sector. Major educational centers, such as the Vietnam National University of Agriculture, are actively organizing extensive technological and job fairs to connect biotechnology graduates and innovative nano-agri products directly with leading agribusinesses, fostering a robust ecosystem for rapid commercial deployment [45]. Supported by increasing domestic investments and a clear national directive to embrace green biotechnology, Vietnam is rapidly positioning itself not just as a consumer, but as an active innovator and a leading regional hub for the development and application of nanochitosan in sustainable agriculture [24].

7. Conclusion

In summary, chitosan is a versatile biopolymer with considerable potential in sustainable agriculture because of its antimicrobial activity, seed-treatment potential, growth-promoting effects, and ability to enhance plant stress responses. However, its agricultural performance is closely shaped by source, molecular weight, degree of deacetylation, formulation, and application conditions. Among the available sources, fungal chitosan is emerging as a particularly promising alternative because of its fermentation-based production and reduced impurity burden. At the same time, nanochitosan is attracting growing interest as a functional upgrade that may improve dispersion, delivery, and biological efficiency. Even so, major challenges remain in production standardization, formulation consistency, safety evaluation, and field-scale validation. Future research should therefore focus not only on material development, but also on translating laboratory-scale promise into robust and reproducible agricultural applications.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

Author contributions

- Phuong Thi Hai Le: literature collection, manuscript writing (original draft)
- Anh Ngoc Nguyen: manuscript writing (review and editing)
- Nghi Binh Phuong Nguyen: literature collection, proofreading
- Phuc Nguyen Thien Le: manuscript structuring, revision
- Phu H Le: conceptualization, supervision, administration, resources support, critical revision

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