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REVIEW

Eco-Friendly Synthesis of Chitosan: Biological Properties and Plant Protection Applications

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ABSTRACT: Plant protection is essential for safeguarding global food security, as plant pathogens and diseases are among the major causes of annual crop losses worldwide. Conventional chemical pesticides have been extensively employed to manage these challenges; however, their intensive and indiscriminate use can pose serious risks to human health, animal welfare, and environmental quality. Therefore, the development of safer, eco-friendly, and sustainable alternatives has become increasingly imperative. In this regard, natural biopolymers have shown promise as candidates for sustainable plant protection strategies. Chitosan (CTS), a natural biopolymer derived primarily from the deacetylation of chitin (CTN) obtained from crustacean shells, insects, and fungal cell walls, has attracted considerable attention due to its remarkable biological properties. However, conventional CTS extraction relies on chemical processes that can negatively affect the environment and human health. Thus, green extraction approaches have attracted considerable interest as simpler, more economical, and environmentally safer methods for biopolymer production. Green-synthesized CTN and its derivative CTS exhibit promising antimicrobial activity against several phytopathogens through dual mechanisms involving direct pathogen inhibition and indirect stimulation of plant immune responses, making them potential alternatives to synthetic agrochemicals. This review provides a comprehensive assessment of the sources, physicochemical characteristics, and green extraction approaches of CTN and CTS, with particular emphasis on their antimicrobial efficacy and applications in sustainable plant protection. Their favorable biocompatibility further broadens their applicability in agricultural, pharmaceutical, and food preservation sectors. Green synthesis approaches represent a significant advancement toward sustainable biopolymer production. Nevertheless, further research is required to optimize extraction processes, enhance bioactive performance, and elucidate mechanisms of action, thereby realizing their potential as multifunctional agents for plant health and broader biotechnological applications.

KEYWORDS: Biopolymers; natural products; antimicrobial agents; plant protection; degree of deacetylation; biopesticide; induced systemic resistance

1 Plant Protection Strategies

Plant protection is a critical scientific discipline that employs an integrated combination of chemical, biological, cultural, and physical strategies to prevent and control diseases, pests, and weeds, thereby safeguarding plant health and ensuring sustainable agricultural productivity [1,2]. The importance of this

field is related to its direct impact on global food security and economic stability, as plant pests and diseases are responsible for causing losses of about 40 percent of annual global crop production [3]. Therefore, effective threat management and plant protection practices can enhance crop yield and quality while benefiting human health and environmental sustainability. Moreover, integrated plant protection strategies, such as Integrated Pest Management (IPM), are crucial for preventing pathogen spread through early intervention and eco-friendly approaches, thereby maintaining healthy agroecosystems and supporting sustainable food production for the growing global population [4].

Plant protection strategies include chemical, physical, cultural, and biological methods. Chemical approaches, particularly pesticides such as insecticides, fungicides, and herbicides, provide rapid and effective large-scale pest control but may pose environmental risks [3]. Cultural methods include crop rotation, proper irrigation, and the use of resistant varieties, offering economical and sustainable approaches that improve long-term soil health. Physical and mechanical methods, such as removing infected plants and using field traps, minimize environmental impacts and chemical residues, making them particularly suitable for organic farming systems [2]. Regarding biological plant protection, these methods utilize biocontrol agents, such as beneficial microorganisms, thereby reducing chemical pesticide use, protecting indigenous microorganisms, minimizing human health risks, and promoting environmental sustainability [4]. On the other hand, IPM strategies aim to balance productivity with ecological sustainability by integrating these approaches in a harmonious and balanced manner to achieve effective and promising results.

2 Disadvantages of Traditional/Chemical Strategies

Although chemical methods such as synthetic pesticides are effective and give rapid pest control, they cause serious environmental and health risks, including contamination of soil, water, and air. They may also cause direct toxicity to farmers and consumers due to the accumulation of harmful residues in food products. They can also harm beneficial soil microorganisms and natural enemies. Furthermore, with continued use, they can lead to pest resistance [5].

3 Green Sustainable Plant Protection Strategies

Green or sustainable plant protection methods have gained increasing attention in recent years because of the significant environmental and health concerns associated with conventional chemical-based approaches. These sustainable strategies encompass a wide range of alternatives, including biological control agents, cultural practices, botanical pesticides, plant extracts, essential oils, biopolymers, and microbial- and plant-derived secondary metabolites. Such approaches can provide effective protection against a broad range of agricultural pests and pathogens while reducing dependence on synthetic pesticides [6]. In contrast to conventional chemical treatments, green plant protection methods can minimize environmental pollution and reduce the risks of toxic residues affecting humans, animals, and non-target organisms. They can also contribute to the conservation of biodiversity by protecting beneficial insects, soil microorganisms, and other organisms that play important roles in maintaining healthy agroecosystems. Moreover, the integrated use of sustainable approaches may help reduce the development of pest and pathogen resistance, which is an increasing challenge associated with repeated pesticide application [5,6].

In the long term, sustainable plant protection strategies can contribute to maintaining soil health and productivity, improving crop quality and production, and enhancing food safety. Therefore, their integration into modern agricultural systems represents an important step toward environmentally responsible, economically viable, and sustainable crop production [7].

4 Natural Products in Plant Protection

Natural products have emerged as safe, green and sustainable plant protection methods that offer a suitable alternative to synthetic chemical pesticides. Derived from plants, microorganisms, or minerals, natural products such as plant extracts, essential oils, and microbial metabolites, some of which are already formulated and registered for use in local markets, are widely recognized for their biodegradability, low toxicity to non-target organisms, and reduced environmental persistence [8]. These renewable compounds selectively target phytopathogens while preserving beneficial insects and soil microbiota, offering safer applications for farmers and consumers [9]. For these reasons, integrating natural products into plant protection programs can contribute to environmental health, crop health, and soil productivity while supporting the principals of IPM and organic farming systems.

5 Polymers and Biopolymers in Plant Protection

A polymer is a natural or synthetic substance composed of macromolecules, very large molecules formed by the repeated bonding of smaller units called monomers [10]. Many essential components of living organisms, such as proteins, cellulose, and nucleic acids, are polymers. Polymers play a key role in numerous man-made materials, including plastics, rubber, and paper [11].

Biopolymers (BPs) are a subclass of natural polymers produced by living organisms including plants, animals, and microorganisms. Biopolymers are characterized by their renewability, biodegradability, and biocompatibility [12]. In the context of sustainable plant protection, biopolymers have gained significant attention as eco-friendly alternatives to synthetic materials [13]. Among the most promising BPs used for plant protection are chitosan (CTS), lignin, alginate, cellulose derivatives and starch-based polymers. Alginate is a seaweed-derived polysaccharide known for forming hydrogels and encapsulating bioactive compounds for controlled release [14]. Cellulose derivatives are modified plant-based materials used in biodegradable films and coatings for seeds and fruits [15]. Starch-based polymers are obtained from crops such as corn and potato, and are widely applied in slow-release fertilizers and pesticides [16].

Chitosan is a linear polysaccharide generated through the deacetylation of chitin (CTN), primarily obtained from crustacean shells such as crabs and shrimp; it is widely used in agriculture for its antimicrobial and plant resistance-enhancing properties [17]. These BPs are able to reduce chemical usage, improve plant growth and soil health, and provide a safe, eco-friendly alternative to synthetic materials. They also act as carriers for agrochemicals and beneficial microbial agents to protect seeds from environmental stress and pathogens [18].

6 Chitin and Chitosan as Eco-Friendly Biopolymers

Chitin, a linear polysaccharide composed of β-(1→4)-linked N-acetylglucosamine units, is one of the most abundant biopolymers in nature [19]. Chitin exhibits exceptional biocompatibility, biodegradability, and versatility, making it a promising candidate for diverse applications ranging from the biomedical to the environmental sector [20,21]. Chitin has recently emerged as a subject of great interest as a natural alternative for synthetic substances used in agro-pharmaceutical fields. Chitosan, derived from CTN through deacetylation, is a linear polysaccharide composed of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units [19]. Chitosan has been widely used in several applications in various fields, due to its biocompatibility, biodegradability, antimicrobial activity, and non-toxic nature [20,21].

Conventional CTN extraction methods typically rely on harsh chemicals and energy-intensive processes, raising environmental sustainability concerns [22]. Chitin is commonly extracted from crustacean shells through a sequence of demineralization and deproteinization steps [12,17]. Demineralization is

usually performed using strong acids, particularly hydrochloric acid, to dissolve calcium carbonate and other mineral components. This is followed by deproteinization, often using concentrated sodium hydroxide at elevated temperatures, to remove proteins and other organic materials. The resulting CTN can then be converted into chitosan through deacetylation using concentrated alkaline solutions, generally sodium hydroxide, under high temperatures for several hours [17]. These methods have several disadvantages due to the use of large quantities of acids and alkalis, which generate chemical wastewater that requires neutralization and proper treatment [22]. In addition, prolonged heating and repeated washing steps increase energy and water consumption. Harsh chemical conditions may also cause polymer degradation, potentially affecting the functional properties of the resulting CTN or CTS. Chemical storage, handling, and accidental releases may further create risks of soil and water contamination. Therefore, improper management of extraction wastes can contribute to water pollution, resource depletion, and greenhouse-gas emissions, highlighting the need for safer and more sustainable extraction technologies [23].

In contrast, green synthesis offers a promising alternative strategy, utilizing renewable resources and eco-friendly methods to efficiently convert CTN into CTS [24]. Green synthesis of CTN and CTS includes: (i) enzymatic hydrolysis; (ii) biotechnological methods; and (iii) ionic liquid-assisted synthesis. Enzymatic hydrolysis employs protease to deproteinize the matrix and obtain pure CTN, while chitinase disrupt its crystalline structure and expand the surface area, thereby enhancing the efficiency of subsequent deacetylation into CTS [25]. Meanwhile, biotechnological methods utilize microbial fermentation processes to produce CTN and CTS from low-cost substrates, such as crustacean shell waste and other agro-industrial by-products [26,27]. Additionally, several fungal species, like Aspergillus, can synthesize CTN in a more sustainable manner by leveraging their natural metabolic pathways [28]. Regarding ionic liquid-assisted synthesis, this approach utilizes ecologically safe ionic liquids to dissolve CTN for its subsequent conversion into CTS [29].

This method enables a more efficient and safer extraction process compared to conventional approaches. This review aims to provide a comprehensive overview of CTN and CTS, with a particular focus on their green-synthesis, natural sources, physicochemical characteristics, potential applications, their role in plant resistance against phytopathogens, and future prospects.

6.1 Chemical Structure and Properties of Chitin

Chitin is a long-chain polymer composed of repeating N-acetylglucosamine (GlcNAc) units, connected by β-(1→4) glycosidic bonds [19,30,31]. The structure of CTN (Fig. 1A) is similar to cellulose (Fig. 1B), with the difference that the hydroxyl group (-OH) at the C-2 position of the glucose monomer in cellulose is replaced by an acetamido group (-$NHCOCH_3$) in CTN [32,33], giving CTN distinct properties and rendering it water-insoluble and resistant to degradation by numerous enzymes that typically break down cellulose.

The chemical structure of CTN can be represented as $[\rightarrow 4)$-β-D-GlcNAc-$(1\rightarrow]_n$, where GlcNAc represents N-acetylglucosamine and (1→4) indicates the glycosidic linkage between adjacent GlcNAc units (Fig. 1A). An expanded representation of the repeating structure is [→4)-β-D-GlcNAc-(1→4)-β-D-GlcNAc-(1→4)-β-D-GlcNAc-(1→]. The degree of polymerization (n) can vary widely, resulting in CTN molecules of different chain lengths.

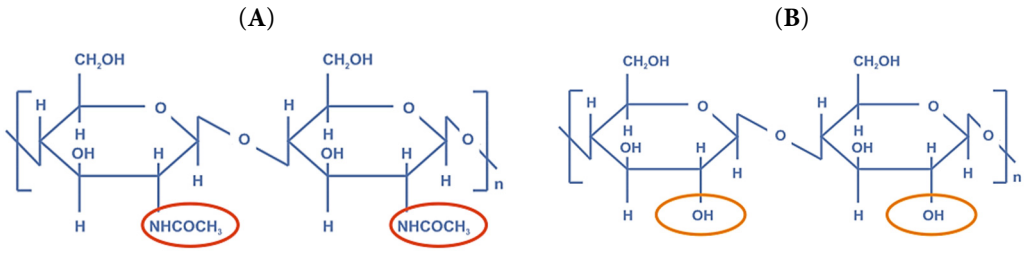

Figure 1: Chemical structure of chitin (**A**) and cellulose (**B**) [32].

Chitin is a major structural component of arthropod exoskeletons (such as insects, crustaceans, and arachnids), the radula of mollusks, and the cell walls of fungi [34]. It provides rigidity and protection to these organisms, similar to the role of cellulose in plants. Chitin possesses diverse properties that render it a valuable material for numerous potential applications [21,35]. The principal properties of CTN are summarized in Table 1.

Biocompatibility. Chitin is biocompatible, meaning it is well-tolerated by living organisms without eliciting significant immune responses or adverse reactions [36]. This property renders CTN suitable for various biomedical applications, including tissue engineering; wound healing, and drug delivery.

Biodegradability. Chitin is biodegradable under certain conditions, particularly in the presence of chitinolytic enzymes produced by bacteria, fungi, and some marine organisms [37]. This property facilitates the sustainable disposal of CTN-based materials, thereby mitigating their environmental impact on ecosystems.

Chemical versatility. Chitin can be chemically modified through processes such as deacetylation, crosslinking, and derivatization to produce CTS [19,38]. These processes can alter CTN's physicochemical properties, such as solubility, charge density, and mechanical strength, expanding its range of potential applications.

Insolubility in water. Chitin is insoluble in water and most organic solvents due to the strong intra- and intermolecular hydrogen bonds between its polymer chains [21]. This property contributes to its durability and resistance to degradation, making it suitable for applications that require water resistance, such as in bioplastics and protective coatings [39].

Absorbency. Chitin possesses the ability to adsorb and retain oils, owing to its fibrous/porous structure and surface characteristics, making it a potential material for oil sorption and oil–water separation applications [40].

This property, coupled with its biocompatibility and biodegradability, makes CTN-based materials suitable for use in absorbent hygiene products, environmental remediation, and controlled release formulations [41].

Renewability. Chitin is primarily a byproduct of seafood processing and fungal fermentation [20]. Its renewable nature makes it an attractive alternative to synthetic materials derived from non-renewable resources, contributing to the development of sustainable technologies and products.

Biological functionality. Chitin and chitin-derived oligosaccharides have diverse biological functions, including defence against pathogens, regulation of developmental processes, and mediation of interactions with symbiotic microorganisms [41]. These biological properties contribute to the ecological significance and potential applications of CTN in biotechnology and agriculture. The derivative chitosan exhibits inherent antimicrobial properties, attributed to its cationic nature and its ability to interact with microbial cell walls [42,43]. This antimicrobial activity makes CTN and its derivatives promising candidates for applications in the biomedical, food and agricultural fields.

The combination of the above-mentioned properties makes CTN a versatile and valuable biomaterial with diverse applications across the biomedical, environmental, agricultural, and industrial sectors [34]. Further research remains necessary to fully explore its potential and address various societal and environmental challenges.

Table 1: Chemical Structure and Properties of Chitin.

Property	Definition/Description	Effect on Bioactivity	References
Chemical Structure	Long-chain polymer of repeating N-acetylglucosamine (GlcNAc) units linked by β-(1→4) glycosidic bonds and has acetamido group (-$NHCOCH_3$) at C-2.	The rigid, highly hydrogen-bonded structure limits bioactivity in native form, but provides a strong base for chemical deacetylation to CTS that enhance bioactivity.	[19,30]
Biocompatibility	Well-tolerated by living organisms; does not cause harmful side effects.	Promotes cell adhesion, proliferation, and tissue integration, making it bioactive in wound healing without leading to chronic inflammation.	[36]
Biodegradability	Degraded by chitinolytic enzymes into harmless oligosaccharides.	The breakdown products (such as chitooligosaccharides) can help regulate the immune system and act as antioxidants, promoting the activity of macrophages and the production of cytokines.	[37]
Chemical Versatility	Can be modified by acetylation, crosslinking, and deacetylation to produce CTS.	Allows introduction of bioactive functional groups (e.g., carboxyl, amine) that enhance interactions with cells, enzymes, and microbial membranes.	[19,38]
Insolubility in Water	Insoluble in water and most organic solvents due to strong intra- and intermolecular hydrogen bonding.	Limits direct bioactivity in aqueous biological fluids, but enables sustained-release formulations where the material degrades slowly, prolonging its bioactivity.	[21,39]
Absorbency	Ability to absorb and retain water, oils, and other liquids.	High absorbency facilitates retention of growth factors, drugs, creating a moist, bioactive environment that accelerates healing and reduces infection risk.	[40]
Renewability	Derived as a byproduct of seafood processing and fungal fermentation; a sustainable biomaterial.	Renewable sources ensure consistent, low-cost production of bioactive derivatives (e.g., CTS, oligomers) for large-scale biomedical use.	[20]
Biological Functionality	Involved in defence against pathogens, regulation of morphogenesis, and mediation with symbiotic microorganisms in nature.	Able to recognize pathogens and activate plant defenses and supporting gut health.	[41]
Antimicrobial Activity	Promising antimicrobial properties due to its cationic nature and interaction with microbial cell walls.	The positive charge interacts with negative charge on cell membrane of microorganism, leading to leakage of cytoplasmic components and growth inhibition.	[42,43]

6.2 Chemical Structure and Properties of Chitosan

Chitosan is a linear polysaccharide composed of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units as illustrated in Fig. 2. It is derived from the deacetylation of CTN (Fig. 2), a structural component found in the exoskeletons of crustaceans, insects, and fungal cell walls [21]. The degree of deacetylation refers to the proportion of glucosamine units relative to the total number of glucosamine and N-acetylglucosamine units. The degree of deacetylation significantly influences the physicochemical properties of CTS. Higher degrees of deacetylation are associated with increased solubility, charge density, and bioactivity [21]. Understanding the chemical structure and properties of CTS is key to modifying its characteristics for targeted applications and designing novel materials with enhanced functionality [21].

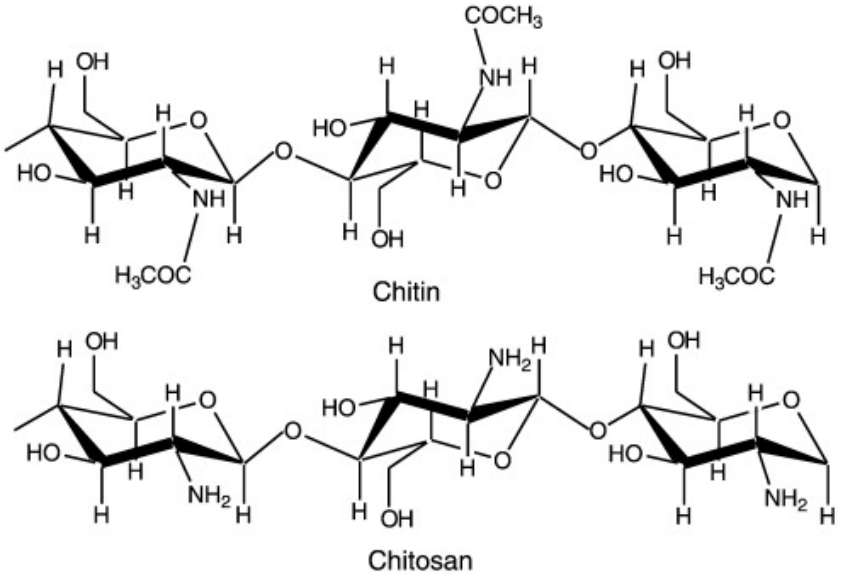

Figure 2: Chemical structure of chitin and deacetylated chitosan [31].

The common characteristics of CTS include biocompatibility, pH, sensitivity, gelation, mucoadhesive properties, biodegradability, film-forming capacity, and antimicrobial efficacy (Table 2).

Biocompatibility. Chitosan is biocompatible, non-toxic, and biodegradable, making it suitable for various biomedical applications such as drug delivery, tissue engineering, and wound healing [44]. Its biocompatibility closely resembles that of natural glycosaminoglycans found in the extracellular matrix (ECM).

pH sensitivity. Chitosan is pH-sensitive, undergoing protonation in acidic environments due to the presence of primary amino groups. The pH responsiveness is exploited in drug delivery systems to achieve controlled release of therapeutic agents in response to changes in pH within the body [45].

Gelation. Chitosan can undergo gelation through physical or chemical crosslinking, forming hydrogels with tunable mechanical properties [46]. Chitosan hydrogels find applications in tissue engineering, and other medical uses as scaffolds or carriers for therapeutic agents [47].

Mucoadhesion. Chitosan possesses mucoadhesive properties, allowing it to adhere to mucosal surfaces [48]. This property is exploited in pharmaceutical formulations for targeted drug delivery to mucosal tissues such as the gastrointestinal tract and nasal cavity [49].

Biodegradability. Chitosan is biodegradable under physiological conditions due to enzymatic degradation by lysozyme, saliva, and other enzymes. Its biodegradability facilitates the safe clearance of CTS-based materials from the body after use, minimizing environmental impact [50].

Film-forming ability. Chitosan can form transparent, flexible films through solvent casting or film-deposition techniques. These films exhibit effective barrier properties against gases and moisture, making them suitable for the food-packaging and pharmaceutical industries [51].

Regarding plant protection, the chemical properties of CTS makes it highly suitable for plant protection applications. The main functional groups present are hydroxyl (–OH) and amino ($–NH_2$) groups, with the degree of deacetylation and molecular weight strongly influencing its solubility, charge density, and biological activity [21]. Under acidic conditions, the amino groups become protonated ($–NH_3^+$), giving CTS a positive charge that facilitates electrostatic interactions with negatively charged microbial cell membranes [52,53], increasing membrane permeability, causing leakage of intracellular components, and inhibiting the growth of pathogens. Chitosan and especially chitosan oligosaccharides can also act as elicitors, stimulating defense-related responses such as the production of reactive oxygen species, phenolic compounds, phytoalexins, and defense enzymes, thereby enhancing plant resistance to pathogens [54,55].

Furthermore, the chemical versatility of CTS allows it to be incorporated into composite materials, hydrogels, and nanoparticles, improving its stability, controlled-release properties, and adhesion to plant surfaces [56]. Chitosan-based nanoparticles and hydrogels can serve as carriers for antimicrobial agents or bioactive compounds, while composites can provide sustained protection and improve delivery efficiency [57].

Table 2: Chemical Structure and Properties of Chitosan.

Property	Definition/Description	Effect on Bioactivity	Reference
Chemical Structure	Linear polysaccharide of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units. Derived from deacetylation of chitin. Contains free primary amino groups ($-NH_2$).	Its positively charged amino groups help it interact with negatively charged cell membranes, DNA, and proteins, improving its antimicrobial, gene delivery, and mucoadhesive properties.	[21]
Degree of Deacetylation (DDA)	Proportion of glucosamine units relative to total units. Higher DDA is more free amino groups.	Higher DDA increases charge density, leading to stronger antimicrobial activity, better mucoadhesion, and enhanced cell compatibility.	[21]
Biocompatibility	Non-toxic and biodegradable. Structurally similar to natural glycosaminoglycans (e.g., hyaluronic acid) in the extracellular matrix.	Promotes cell attachment, proliferation, and differentiation without toxicity. Its similarity to ECM components enables bioactive signalling that supports tissue regeneration and reduces fibrotic capsule formation.	[44]
pH Sensitivity	Undergoes protonation in acidic environments (pH < 6.5) due to primary amino groups, becoming soluble and positively charged.	Enables pH-triggered bioactivity: in inflamed/infected tissues (lower pH), CTS becomes more cationic, enhancing antimicrobial action and controlled drug release exactly at the target site.	[45]
Gelation	Forms hydrogels via physical or chemical crosslinking, with tunable mechanical properties.	Hydrogels provide a 3D bioactive scaffold that mimics native ECM, supports cell encapsulation and growth, and allows controlled delivery of growth factors, directly impacting tissue regeneration and wound healing efficacy.	[46]

Table 2: *Cont.*

Property	Definition/Description	Effect on Bioactivity	Reference
Mucoadhesion	Adheres strongly to mucosal surfaces via electrostatic interactions with negatively charged mucin glycoproteins.	Prolongs residence time at mucosal sites, enhancing local bioavailability of drugs and vaccines.	[49]
Biodegradability	Degraded enzymatically by lysozyme, salivary enzymes, and colonic microflora into non-toxic oligosaccharides.	Degradation products are bioactive and exhibit antioxidant and anti-inflammatory, and prebiotic activities, and can modulate immune responses.	[50]
Film-Forming Ability	Forms transparent, flexible films with effective gas and moisture barrier properties.	Films can be loaded with bioactive agents (e.g., antimicrobials, growth factors). The film itself acts as a physical barrier, while releasing actives in a controlled manner, enhancing wound healing and food preservation bioactivity.	[51]
Antimicrobial Activity	Polycationic nature disrupts microbial cell membranes, leading to leakage of intracellular components. It is effective against bacteria, fungi, and some viruses.	Degree of activity depends on molecular weight and DDA. Higher charge, stronger membrane disruption. It enables applications in antimicrobial coatings, and food preservation without synthetic antibiotics.	[52,53]

6.3 Natural Sources of Chitin and Chitosan

Natural sources of CTN and CTS include various organisms from marine, terrestrial, and fungal environments (Fig. 3). These natural sources provide raw materials for CTN and CTS extraction, which can be processed for biological applications in various fields such as medicine, agriculture, food and cosmetics. The choice of extraction source depends on several factors such as availability, sustainability, cost and the desired properties of the final product.

Figure 3: Natural sources of chitin. Where (**a**) insects; (**b**) crustaceans; (**c**) arachnids; (**d**) fungi.

Crustacean. Crustaceans such as shrimp, crab, lobster, and krill are abundant sources of CTN [58]. Chitin is a major component of their exoskeletons, whereas CTS can be obtained from CTN through deacetylation processes [21]. Chitosan derived from crustacean sources typically possesses a high molecular weight (approximately 1.5×10^6 Da) [58]. In addition, crustacean-derived CTS exhibits a highly crystalline structure with tightly packed molecules, resulting in lower solubility and consequently, reduced bioactivity. The environmental concerns stem from the chemical-intensive extraction process of crustacean-derived CTS, as well as the potential risks posed by crustacean-associated allergens. While this type of CTS is commonly used in agriculture, water treatment, and food preservation, it is less suitable for advanced medical applications due to its lower purity and the presence of residual contaminants [59].

Insects. Insects such as beetles, ants, and butterflies have exoskeletons composed primarily of CTN [60]. Recent studies have demonstrated that insect-derived CTS has a degree of deacetylation within the range of 85–90% and a molecular weight values ranging from 30 to 300 kDa [61]. Another study conducted by Khayrova et al. [62] reported that the molecular weight of CTS extracted from *Hermetia illucens* ranged between 480–570 kDa and its degree of deacetylation was in the range of 87–92%. A recent study by Triunfo et al. [63] investigated the production and characterization of CTN and CTS from the adult and pupal exuviae of *H. illucens*. The researchers found that pupal exuviae provided the most suitable biomass for CTN and CTS yields due to their abundance and ease of supply. Furthermore, the resulting CTS demonstrated a lower molecular weight, a high degree of deacetylation, and potential antimicrobial properties.

Fungi. Chitin is a key-component of the fungal cell wall, making its extraction easier and more sustainable [64]. Mushrooms such as *Agaricus bisporus* (button mushroom) [65], *Pleurotus ostreatus* (oyster mushroom) [66], and *Ganoderma lucidum* (reishi mushroom) [67] as well as other fungi such as *Penicillium* sp., *Aspergillus* sp., *Rhizopus* sp., and others, are examples of fungal sources of CTN. Chitosan can be derived from CTN extracted from these fungi through deacetylation [68–70].

Fungal CTS is typically characterized by a lower molecular weight (100–300 kDa) and a higher deacetylation degree (around 80% or more) [68]. It is often less crystalline and more hydrated, resulting in increased solubility and reactivity. Its production is environmentally friendly, thereby reducing the ecological impact during cultivation. Additionally, the higher purity and bioactivity of fungal CTS make it suitable for medical and pharmaceutical applications [71].

The extraction of CTN from fungi is particularly significant because the resulting CTN/CTS exhibits distinct advantages, including a relatively low molecular weight compared with conventional crustacean-derived chitosan; however, its molecular weight varies considerably depending on the fungal species and processing conditions [72,73]. Chitosan can be extracted from fungi without the need for a demineralization phase, and the raw materials are inexpensive, sustainable and readily available throughout the year [74]. Due to these advantages, fungal CTS stands out for its eco-friendly production and suitability for agricultural and medical applications, while crustacean CTS dominates industrial sectors.

Several studies have reported that the mycelium of various fungi, including *Absidia* sp., *Aspergillus* sp., *Mucor* sp., *Pleurotus* sp., *Ganoderma* sp., *Rhizopus* sp., and *Trichoderma* sp., has been identified as alternative CTN source due to the abundance of CTN in their cell walls [73,75].

6.4 Methods of Green Synthesis of Chitin and Chitosan

Green-synthesis methods for CTN and CTS involve environmentally friendly approaches that minimize the use of hazardous chemicals, energy consumption, and waste generation [76]. Some common green-synthesis methods, illustrated in Fig. 4, used for CTN and CTS productions are discussed below:

Biological extraction. This method employs enzymes or microorganisms through microbial fermentation to break down the protein and mineral components of natural sources, such as crustacean shells or fungal cell walls, resulting in CTN-rich materials [46–48]. Biological extraction is considered a green method because it utilizes natural processes and reduces the reliance on harsh chemicals.

Ionic liquid processing. Ionic liquids are solvents composed entirely of ions and are considered green alternatives to traditional organic solvents due to their non-volatility and recyclability [29,77]. Ionic liquids have been explored for their ability to dissolve CTN and CTS, enabling more environmentally friendly extraction and modification processes. For example, Setoguchi et al. [78] extracted CTN from crab shells using a direct extraction method involving the ionic liquid 1-allyl-3-methylimidazolium bromide, followed by demineralization with citric acid.

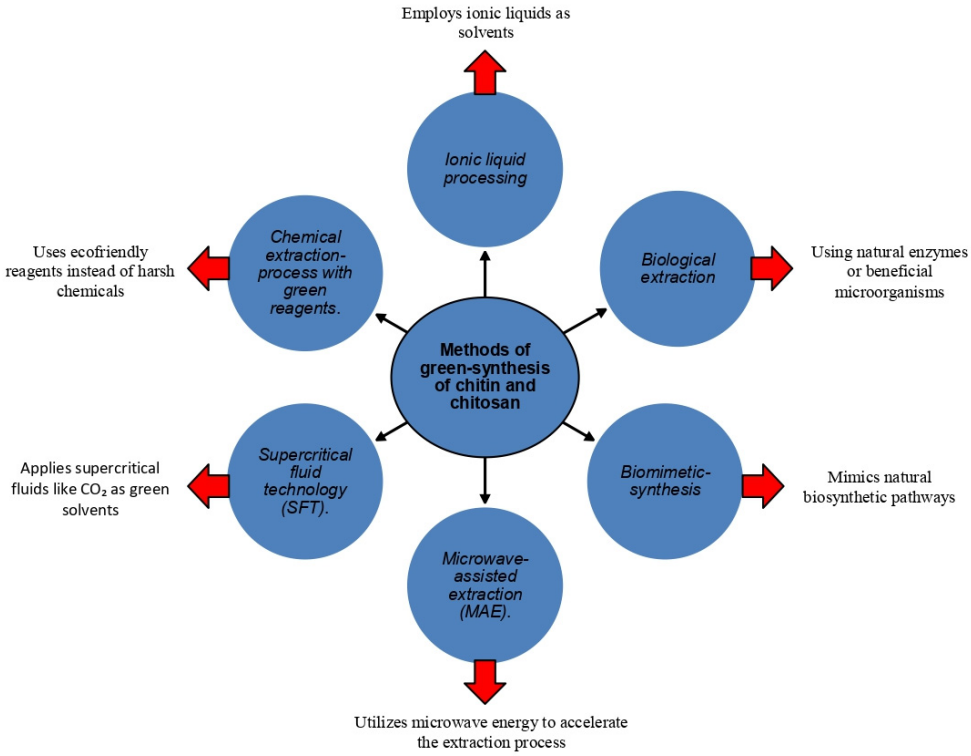

Figure 4: Methods of green-synthesis of chitin and chitosan.

Microwave-assisted extraction (MAE). MAE can be employed to extract CTN and CTS from natural sources using less energy and shorter extraction times compared to conventional methods [79]. This method can enhance the efficiency of extraction while reducing environmental impact.

Chemical extraction process with green reagents. Green synthesis can involve the use of eco-friendly reagents during post-extraction functionalization and chemical modification of CTN and CTS. In particular, these modifications include grafting, acylation, and cross-linking, which can be employed using non-toxic or renewable chemicals to improve the properties of extracted CTN and CTS for specific applications [80].

Supercritical fluid technology (SFT). SFT utilizes substances such as carbon dioxide (CO_2) in their supercritical state and offers a potentially green approach to CTN processing [81]. Rather than directly solubilizing chitin, supercritical CO_2 can be employed as a pretreatment or auxiliary process to remove lipids, disrupt the structure of natural sources, and facilitate subsequent demineralization and deproteinization.

Biomimetic synthesis. Biomimetic approaches mimic natural biological processes to synthesize CTN and CTS-like materials [82]. These methods aim to replicate the conditions found in living organisms to produce CTN and CTS with properties closer to those of their naturally occurring counterparts. In general, green synthesis approaches offer sustainable alternatives to traditional methods of CTN and CTS production, aligning with principles of green chemistry and promoting environmental sustainability in biomaterials research and industrial applications.

6.5 Properties of Green-Synthesized Chitin and Chitosan

The properties of CTN and CTS can be significantly influenced by the synthesis method. Green-synthesized CTN and CTS can offer several advantages over their chemically-synthesized counterparts, particularly in terms of environmental impact, purity, and bioactivity, as discussed below:

Environmental impact. Green synthesis employs eco-friendly approaches, including enzymatic processes, microbial fermentation, and ionic liquids, which reduce chemical waste, minimize toxic byproducts, and support sustainable production. In contrast, conventional chemical synthesis often relies on harsh reagents, such as acids and alkalis (e.g., HCl and NaOH), generating substantial waste and potentially causing environmental pollution and hazards [83].

Purity. Green synthesis generally aims to produce higher-purity CTN and CTS because mild processing and extraction conditions help preserve the native structure of these biopolymers while minimizing degradation and unwanted byproducts. Moreover, the use of environmentally friendly reagents can reduce the formation of residual contaminants. In contrast, chemical synthesis may result in lower product purity due to residual strong acids or alkalis used during demineralization and deproteinization, potentially causing contamination of the final product [84].

Protein and ash content. Protein and ash contents are important indicators of the purity and quality of chitin and chitosan. Green extraction methods generally achieve lower residual protein and ash contents under milder processing conditions, whereas conventional chemical methods can provide more effective deproteinization and demineralization but may involve harsh reagents and generate chemical residues [85,86]. The residual protein and mineral content can influence polymer purity, molecular interactions, and ultimately the antimicrobial performance of chitin and chitosan.

Biocompatibility and bioactivity. Green synthesis may offer enhanced biocompatibility and retains more natural bioactive compounds due to milder processing. This makes green-synthesized CTS more suitable for biomedical applications such as tissue engineering, wound healing, and drug delivery [84]. Chemical synthesis can also produce biocompatible CTS; however, harsh processing conditions may degrade bioactive compounds, potentially reducing its overall effectiveness in biological applications [83].

Molecular weight & degree of deacetylation. Green synthesis can produce CTN and CTS with relatively higher and more consistent molecular weights and a better-controlled degree of deacetylation, helping preserve their structural integrity and enhancing their mechanical properties, solubility, and functional versatility for various applications [87]. In contrast, conventional chemical synthesis may cause greater variations in molecular weight and degree of deacetylation because of harsh chemical treatments, which can promote polymer degradation and consequently affect solubility, viscosity, biological activity, and overall performance [88].

Solubility. Green synthesis may result in improved solubility under certain conditions due to limited chemical modification and milder processing conditions, which help preserve the polymer chains and functional groups [79]. In contrast, chemical synthesis may result in reduced solubility under certain conditions due to degradation or unintended cross-linking resulting from harsh chemical treatments [83].

Biological properties. Green synthesis can better preserve the antimicrobial and antioxidant properties of CTN and CTS because mild processing conditions help retain naturally occurring bioactive compounds and functional groups [89]. In contrast, conventional chemical synthesis may reduce these biological activities because harsh processing conditions can cause degradation or loss of bioactive molecules, potentially affecting the overall functional performance and therapeutic or agricultural applications of the resulting biopolymers.

Cost and scalability. Green synthesis, such as enzymatic hydrolysis or microbial fermentation, may be more expensive or more challenging to scale up than chemical processes [90]. In contrast, chemical synthesis is more cost-effective for large-scale production; however this may compromise environmental sustainability.

The physicochemical characteristics of CTN and CTS extracted using green and conventional methods such as, molecular weight, degree of deacetylation, protein and ash contents, and solubility, are closely

associated with their antimicrobial activity. In particular, a higher degree of deacetylation generally increases the number of positively charged amino groups, enhancing electrostatic interactions with negatively charged microbial cell surfaces. These interactions can promote membrane disruption, cellular leakage, and inhibition of microbial growth, thereby enhancing antimicrobial efficacy against important phytopathogens.

6.6 Factors Influencing Chitosan Bioactivity

Several factors influence the bioactivity of green-synthesized CTS, affecting its performance in various applications such as medicine, agriculture, and food preservation. The key factors affecting CTS bioactivity are discussed below.

Sources. The antimicrobial efficacy of CTS varies significantly depending on its source. Amor et al. [91] emphasized that the source, degree of deacetylation, and molecular size must be carefully selected to target specific pathogens. Chien et al. [92] reported that crab-shell CTS exhibited higher antimicrobial activity than fungal-derived CTS, a finding attributed to its distinct physicochemical properties—including high nitrogen content, optimal degree of deacetylation, solubility, viscosity, and enhanced antibacterial activity [93]. Conversely, fungal CTS is characterized by low molecular weight and high degree of deacetylation [63], and has been shown to exhibit stronger inhibitory effects against Gram-positive than Gram-negative bacteria [94]. Recently, Camele et al. [95] demonstrated that fungal CTS from *Pleurotus eryngii* exhibits promising biocontrol activity against *Monilinia laxa*, the causal agent of plum brown rot.

Target microorganism. Bacterial cell membranes carry a negative charge due to the highly electronegative groups present in their lipopolysaccharides and phospholipids [96]. In contrast, CTS, which is positively charged due to its protonated amino groups (-NH_3^+), can bind to the bacterial cell wall. This interaction increases membrane permeability, ultimately leading to cell death [86]. On the other hand, due to the different composition of G+ve and G-ve cell walls, the interaction of CTS with these two types of bacteria is different. Some studies have reported that the bactericidal effect of CTS is stronger against Gram-negative (G−) than Gram-positive (G+) bacteria, which may be attributed to the higher affinity of the amino groups of CTS for the negatively charged functional groups present in the bacterial cell wall [94]. In contrast, Hassan et al. [97] reported that G+ve bacteria have thick peptidoglycan layers containing negatively charged teichoic acids which enhance their affinity for positively charged CTS, leading to bacterial cell damage. Conversely, G-ve bacteria possess porin channels in their outer membrane, which may impede the entry of larger CTS molecules. On the other hand, Amor et al. [91] reported that CTS extracted from insects exhibits strong antibacterial activity against both G-ve (*Salmonella typhimurium* and *Pseudomonas aeruginosa*) and G+ve bacteria (*Bacillus subtilis*, *Staphylococcus aureus* and *Listeria innocua*).

Molecular weight. Numerous studies have highlighted the relationship between the antimicrobial activity of CTS and its molecular weight. Chitosan molecules with different molecular weights have been shown to exhibit varying levels of efficacy against different bacterial species [98]. Some studies have reported that high-molecular-weight CTS tends to be more effective against Gram-positive bacteria, acting as a barrier that disrupts nutrient uptake by microbial cells [99]. In addition, Liu et al. [100] reported that low-molecular-weight CTS exhibited greater antimicrobial activity against Gram-negative bacteria because it can more readily penetrate their cell walls. However, the relationship between the molecular weight of CTS and its antimicrobial effectiveness may vary depending on the specific conditions and pathogens being studied. Green synthesis approaches for CTS, such as microbial fermentation, allow control of molecular weight, thereby optimizing its bioactivity for specific industrial and medical applications.

Purity. The purity of CTS significantly impacts its bioactivity, influencing its effectiveness across diverse applications [101]. Higher purity levels reduce the presence of contaminants and toxic residues,

which can otherwise interfere with the biopolymer's interaction with biological systems. Pure CTS exhibits enhanced biocompatibility, promoting superior cell adhesion and biological responses [102]. In antimicrobial applications, purified CTS demonstrates more potent activity against pathogens, as impurities can mask its bioactive sites or diminish its functional properties [59].

6.7 Roles of Chitin and Chitosan in Plant Protection Strategies

Green-synthesized CTN and its derivative, CTS, are gaining attention for their diverse biological applications. Chitin and CTS exhibit antimicrobial properties effective against a broad spectrum of microbial pathogens [99,103]. In addition, CTS induces plant resistance against viral diseases and inhibits the systemic spreading of viruses and viroids [104]. Therefore, CTN and CTS can be effectively used as natural preservatives in the food industry inhibiting the growth of foodborne pathogens and spoilage microorganisms and thus extending the shelf life of perishable foods [105,106]. The most common agricultural applications of CTN and CTS in plant protection and for enhancing plant resistance are summarized as follows:

Biopesticides. Chitin and CTS can be considered promising biopesticides against several pests and crop diseases because of their natural, biodegradable, and low-toxicity properties. They can stimulate plant defense mechanisms, inhibit the growth of pathogenic microorganisms, and reduce pest development. For example, they act as natural insecticides by disrupting the formation and integrity of the insect cuticle during molting, ultimately impairing normal development and potentially leading to mortality. In addition, CTS has been reported to suppress fungal diseases caused by *Botrytis cinerea*, *Fusarium* spp., and *Alternaria* spp., while chitin-based treatments can enhance plant resistance against insects such as aphids and caterpillars. Their ability to promote plant growth and induce systemic resistance makes CTN and CTS valuable alternatives to conventional chemical pesticides.

In particular, CTS possesses antifungal properties that enable the control of several plant fungal diseases [95]. Sun et al. [107] studied the effect of CTN extracted from *Saccharomyces cerevisiae* cell walls on the disease resistance of tomato fruit against *Botrytis cinerea* infection and they found that it significantly enhanced resistance to gray mold rot caused by *B. cinerea*, while promoting the buildup of reactive oxygen species (ROS) and callose deposition.

Soil amendment. Chitin and CTS can be used as soil amendments to improve soil structure and fertility. They can enhance water retention, promote nutrient uptake, and stimulate beneficial soil microorganisms, leading to improved crop yields [108]. Fan et al. [109] demonstrated that crude CTN amendments can alleviate the challenges associated with continuous soybean cropping by raising soil pH and improving N/P/K availability.

Biostimulants. Chitin and CTS have been investigated as biostimulants that, when applied as foliar sprays, enhance root development, nutrient uptake, and tolerance to drought and salinity through physiological stimulation and rapid absorption [110]. When used as seed coatings, CTS can protect seeds against soil-borne pathogens and pests, improves germination rates, seedling establishment, and storage longevity. Zhou et al. [33] reported that nanochitin seed coatings significantly enhanced germination and reduced mean germination time in tobacco. Similarly, Godínez-Garrido et al. [111] found that CTS coatings combined with the fungicide dithiocarbamate had no adverse effects on bean and maize seed germination.

Post-harvest preservation. Chitosan can be applied as a coating for fruits and vegetables to extend their shelf life, reducing microbial spoilage and post-harvest diseases. Abugoch et al. [112] evaluated various coating materials, including CTS, as edible films to extend the shelf life of fresh blueberries and concluded that CTS effectively controlled the growth of molds and yeasts for up to 32 days of storage, compared to untreated control fruits, which showed a significant increase in mold and yeast growth during the same

period. Camele et al. [95] investigated the impact of green-synthesized CTS derived from *Pleurotus eryngii* on fruit quality and its biocontrol efficacy against *Monilinia laxa* infections in plum fruits. The latter study found that the CTS exhibited promising antimicrobial properties, served as a protective agent, reduced moisture loss, and maintained the firmness of the treated plums. Additionally, the treatment with CTS showed significant efficacy against *M. laxa*, leading to a reduction in the percentage of disease infection.

In all cases, the effective and successful translation of the use of CTS into practical plant-protection products depends on several factors, including: formulation, pH stability, and compatibility with other IPM components. Appropriate formulation is essential to improve CTS solubility, stability, and effectiveness under field conditions. Its activity can also vary with pH, making pH stability an important consideration for consistent performance. Furthermore, compatibility with biological control agents, botanical pesticides, and other IPM tools is necessary to ensure that CTS can be integrated effectively into sustainable crop-protection programs.

Several additional factors should be considered when developing CTS-based plant-protection products, as discussed in detail in this review. Among them are molecular weight, purity, and degree of deacetylation, which can affect the efficiency of CTS-formulated products, as well as their solubility, antimicrobial activity, and ability to induce plant defense responses. Newly formulated CTS-based products should be characterized by good adhesion and persistence on plant surfaces and, where appropriate, the ability to penetrate plants tissues. At the same time, they should maintain their activity under variable environmental conditions such as temperature, humidity, and rainfall. Fundamentally, the newly formulated plant-protection products should be evaluated for their compatibility with other IPM components, such as antagonistic microorganisms, plant essential oils and vegetal extracts, and, in some cases, traditional chemical and synthetic conventional pesticides. Regarding the latter, CTS-formulated products should not adversely affect the activity of these components or beneficial organisms. For all these reasons, future studies still need to verify the optimal application rates, conduct open-field evaluations to assess their efficacy, and evaluate their stability during storage and shelf life to ensure their performance and facilitate the practical commercialization of CTS as a sustainable plant-protection product.

6.8 Dual Mechanisms of Chitin and Chitosan in Plant Protection

Chitin and CTS play a vital role in enhancing plant resistance against phytopathogens through a dual-action strategy: they directly interact with pathogens while simultaneously activating the plant's intrinsic immune system. This protective effect operates via two primary pathways.

6.8.1 Direct Antimicrobial Action (First Pathway)

This pathway relies on the intrinsic antimicrobial properties of CTN and CTS, which exhibit potent antiviral, antibacterial, and antifungal activities, making them valuable tools for sustainable agricultural management. They can control plant diseases, interfere with essential cellular processes and inhibit pathogen growth [113]. Their antimicrobial effects arise from CTS's positively charged molecules interacting with negatively charged microbial cell membranes, causing leakage of cellular contents and cell death [114].

Meng et al. [115] highlighted CTS's antifungal activity against *Aspergillus ochraceus*, demonstrating its ability to inhibit spore germination and mycelial growth, indicating potential as a postharvest antifungal agent. In particular, Meng et al. [115] reported that CTS (100 kDa; 93% degree of deacetylation) exhibited strong concentration-dependent antifungal activity against *A. ochraceus*. After 12 h, spore germination decreased from approximately 84% in the untreated control to 36% and 19% following treatment with 0.05% and 0.1% chitosan, respectively. Chitosan also inhibited mycelial growth and induced marked morphological

alterations, including hyphal shriveling, abnormal branching, and vacuolation. Transcriptomic analysis identified 435 differentially expressed genes, indicating disruption of membrane homeostasis and ribosome biogenesis. These findings suggest that chitosan exerts antifungal activity through both structural damage and interference with essential cellular processes.

Chitosan can alter cell permeability, leading to the leakage of intracellular electrolytes and proteins, thereby affecting microbial viability [116]. Additionally, CTS inhibits enzymes like cellulases and pectinases secreted by pathogens that degrade plant cell walls. This inhibition enhances its broader antibacterial properties by reducing pathogen virulence and bolstering plant defence mechanisms against pathogens [117].

As shown in Table 3, several studies have reported the antimicrobial activity of chitosan extracted from various sources—including fungal biomass, insects, and marine crustaceans against a range of microbial pathogens. In particular, fungal-derived chitosan from species such as *Rhizopus oryzae* showed minimum inhibitory concentration (MIC) values ranging from 0.067 to 2 mg/mL against microorganisms such as *Escherichia coli* and *Penicillium verrucosum*. Chitosan derived from *Pleurotus eryngii* showed MIC values ranging from 0.375 to 1.5 mg/mL against some fungal phytopathogens such as *Botrytis cinerea* and *Monilinia laxa*.

Insect-derived chitosan from *Hermetia illucens* exhibited MICs ranging from 0.15 to 0.30 mg/mL against *E. coli* and *Micrococcus flavus*, and 62.5–125 µg/mL against *Staphylococcus epidermidis*. Among marine crustaceans, chitosan from shrimp shell was effective against *Fusarium oxysporum* and *Penicillium digitatum* at 0.5–4 mg/mL, while crab-derived chitosan (from *Polybius henslowii* and commercial crab shell) showed broader antifungal activity with MICs as low as 0.0125 mg/mL against *Cryphonectria parasitica*, *Phytophthora cinnamomi*, *B. cinerea*, and *Heterobasidion annosum* and 0.11–1.8 µg/mL against *B. cinerea* and *F. oxysporum*. The varying MIC values highlight the influence of chitosan source and target pathogen on antimicrobial efficacy.

Table 3: Antimicrobial activity of chitosan extracted from various sources against some phytopathogens.

Chitosan Source		Microbial Pathogen	Range of MIC Values	Reference
Fungal biomass	Zygomycetous fungi: *Rhizopus oryzae*, *Pencillium expansum* and *Aspergillus terreus*	*Escherichia coli* and *Penicillium verrucosum*	0.067–2.0 mg/mL	[118]
	Pleurotus eryngii	*Clavibacter michiganensis*, *Escherichia coli*, *Xanthomonas campestris*, *Penicillium expansum*, *Botrytis cinerea*, and *Monilinia laxa*	0.375–1.5 mg/mL	[95]
Insects	*Hermetia illucens*	*E. coli* and *Micrococcus flavus*	0.15–0.30 mg/mL	[119]
	Hermetia illucens	*Staphylococcus epidermidis*	62.5–125 µg/mL	[62]
Marine crustaceans	Shrimp shell	*Fusarium oxysporum* and *Penicillium digitatum*	0.5–4 mg/mL	[120,121]
	Crab (*Polybius henslowii*)	*Botrytis cinerea*, *Phytophthora cinnamomi*, *Cryphonectria parasitica*, and *Heterobasidion annosum*	0.0125–0.1 mg/mL	[122]
	Commercial crab shell	*Botrytis cinerea* and *Fusarium oxysporum*	0.11–1.8 µg/mL	[62]

6.8.2 Indirect Immune Priming (Second Pathway)

The indirect pathway functions through the stimulation of host plant resistance via several complementary mechanisms, including: (i) induction of plant defence responses, such as induced systemic resistance

(ISR), regulation of reactive oxygen species (ROS) production, and modulation of phytohormonal signalling and crosstalk; (ii) reinforcement of physical barriers like lignin and callose; (iii) modulation of gene expression, leading to the upregulation of defensive genes and the increased activity of pathogenesis-related enzymes; (iv) enhancing production of secondary metabolites; and (v) Modulation of plant-microbiome interactions.

Kaku et al. [123] reported that CTN acts as a potent elicitor of plant defence upon binding to the CTN-elicitor protein located in the plasma-membrane. A chitin oligosaccharide-binding protein has been identified in rice cells, and its presence in other plant species suggests it may act as a receptor involved in plant defence mechanisms [123]. Other studies reported that the application of CTS to plants can induce the expression of defence-related genes, including those encoding pathogenesis-related (PR) proteins, chitinases, and glucanases, as reported by Roby et al. [124].

Trotel-Aziz et al. [125] studied the effect of CTS derived from crab shells on grapevine leaf defence against *Botrytis cinerea* infection and concluded that CTS provided significant protection against grey mould caused by *B. cinerea* under controlled conditions, demonstrating its role as an effective elicitor of defence responses in grapevine leaves and its ability to inhibit the *in vitro* development of *B. cinerea*. More recently, Suarez-Fernandez et al. [126] reported that CTS enhances local defence responses through mechanisms such as stomatal closure, PR protein accumulation, and activation of the MAPK cascade. Additionally, CTS triggers various phytohormone signalling pathways, including salicylic acid, which plays a key role in plant responses to biotic stress. Similarly, Jia et al. [127] showed that CTS oligosaccharide enhances resistance to the tobacco mosaic virus in Arabidopsis by activating the salicylic acid signaling pathway, as evidenced by increased PR1 gene expression and elevated salicylic acid levels in wild-type plants. On the other hand, CTS has been shown to enhance the production of secondary metabolites, including phenolics, flavonoids, and phytoalexins, which play crucial roles in plant defence and stress responses [128] and can also modulate the plant's interaction with beneficial microorganisms in the rhizosphere. It can enhance the colonization of plant roots by plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, which help boost the plant's resistance to pathogens by improving nutrient uptake and inducing systemic resistance.

7 Industrial Challenges in Chitosan-Based Plant Protection

Despite the potential of green-synthesized CTS as a sustainable component of plant-protection products, there are still several challenges that may limit its large-scale application. These include achieving high reaction yields and process efficiency while minimizing energy and water consumption, as well as reducing the need for extensive purification. The cost, availability, and consistent quality of raw materials, together with the recovery or disposal of solvents and biological reagents, can also affect the economic and environmental performance of the process. In addition, standardized characterization of CTS, particularly its molecular weight, degree of deacetylation, purity, and functional performance, is essential to ensure batch-to-batch consistency and reproducible efficacy in plant-protection applications, as discussed in detail in this review. Addressing these challenges is essential for translating laboratory-scale green approaches into reliable, economically viable industrial processes.

8 Conclusion

Chitin and CTS are biopolymers with diverse applications and sustainability benefits, positioning them as valuable resources for several purposes that address environmental challenges. The synthesis of CTN and CTS using green strategies has gained considerable interest in recent years. This review focuses on the efficiency of green extraction methods, the physicochemical and biological properties of the resulting CTN and CTS, and their emerging biomedical, pharmaceutical, and agricultural applications. The findings of this

review highlight that the green synthesis of CTS represents an eco-friendly and sustainable approach to biopolymer production. However, further research is needed to optimize green synthesis methods, improve the properties and performance of CTS, and expand its potential applications across various fields. In particular, green-synthesized CTS has demonstrated significant biological activity, especially antimicrobial properties, highlighting its potential as a promising alternative to conventional synthetic pesticides, which are widely used to control serious plant diseases but may pose risks to human health and the environment.

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