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REVIEW ARTICLE

Biopesticidal potential of insect derived chitosan for crop protection

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Abstract

In recent years, increasing environmental concerns and regulatory restrictions on conventional chemical pesticides have driven the demand for safer, biodegradable and eco-friendly alternatives. Among these, chitosan, a natural polysaccharide derived from the deacetylation of chitin, has gained significant attention due to its broad spectrum antimicrobial, antifungal, antiviral, insecticidal and plant defense inducing properties. Traditionally, chitosan is sourced from marine crustaceans like shrimps and crabs. However, emerging studies have highlighted the untapped potential of insect-based chitosan extracted from species such as *Hermetia illicens* (Black soldier fly), *Bombyx mori* (Silkworm) and *Tenebrio molitor* (Mealworm) as promising biocontrol agents in agriculture. Compared to marine sources, insect derived chitosan offers more advantages which includes all season availability, rapid biomass generation, lower allergenicity and reduced ecological footprints. Insect derived chitosan often shows higher deacetylation and lower molecular weight, enhancing solubility and biological activity against pests and diseases. This review explores the potential of chitosan derived from various insect sources, focusing on its application against a wide range of agricultural pests and phytopathogens. It synthesizes current findings on physicochemical properties, formulation approaches (e.g. nanoparticles, coatings, foliar sprays) and elucidates the mechanisms through which insect-based chitosan disrupts pest physiology, inhibits pathogen growth and elicits systemic resistance in plants. Furthermore, it evaluates the advantages and limitations of insect-sourced chitosan over traditional sources and highlights knowledge gaps, regulatory challenges and future directions for field-level adoption in Integrated Pest Management (IPM) systems.

Keywords: biopesticides; chitosan; crop protection; insect-derived chitosan

Introduction

Modern agriculture faces multiple challenges, such as the overuse of synthetic pesticides, the rapid emergence of resistant pest populations and the degradation of soil and environmental health. Global pesticide use in agriculture reached 3.70 million metric tons (Mt) of active ingredients in 2022, marking a 4% increase from 2021, a 13% rise over the past decade, and more than double the amount used in 1990. India's pesticide use intensity is about 0.5 kg per hectare, significantly lower than countries such as Japan (12 kg/ha), Korea (6 kg/ha) and the USA (4.5 kg/ha). In India, pesticides are applied on only about 25 % of the total cultivated land. The vast majority (about 65 %) of pesticide consumption comprises insecticides with herbicides and fungicides making up most of the remainder. As a result, there is a growing demand for sustainable and eco-friendly alternatives for pest and disease management. Among the promising solutions is chitosan, a biopolymer derived from the deacetylation of chitin, which has received widespread attention owing to its biodegradability, biocompatibility, low toxicity and multifaceted biological activity (1). It is a natural polysaccharide composed of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units. It exhibits antimicrobial, antifungal, antiviral, insecticidal and elicitor properties, making it an ideal candidate for use in integrated pest and disease management strategies (2).

Traditionally, chitosan is extracted from chitin present in marine crustacean shells, shrimp, crab and lobster which are rich in chitosan. Nevertheless, the limited seasonal availability of marine organisms, their high mineral content necessitating intensive demineralization treatments, potential allergenicity and the ecological impact of crustacean processing have driven interest in exploring alternative sources of chitin (3). Nowadays, insects have emerged as a sustainable and underutilized biomass source for chitosan and have attracted significant attention due to their lower ash content, rapid reproduction cycles, lower feed requirements and adaptability to organic waste substrates (4).

Several insect species, including *Hermetia illucens* (Black soldier fly), *Tenebrio molitor* (Mealworm), *Acheta domesticus* (House cricket) and *Bombyx mori* (Silkworm) have shown promise for chitin and chitosan production. The chitosan content in these insects varies considerably based on factors like stage of development, diet and their extraction methodology (5). For instance, the high purity yield of chitosan was yielded in the pupal stage of *Bombyx mori* compared to the higher physiochemical properties of the chitosan extracted from the crustacean (6). Additionally, using insects raised on organic waste substrates supports circular bioeconomy by contributing to both waste reduction and the sustainable production of biomass for biopolymer synthesis (7). In the agriculture sector, the chitosan plays major role in biopesticide, plant immune system elicitors, growth promoter and carrier for agrochemicals. It has the ability to induce systemic acquired resistance (SAR) and activated defense-related enzymes (e.g. peroxidase, phenylalanine, ammonia lyse, chitinase) as documented in a wide range of crops including cereals, vegetables and fruits (8). In pest control, the chitosan interferes with insect molting, disrupts midgut membranes and alters feeding behavior. It also inhibits the germination of fungal spores, limits bacterial colonization and reduces viral replication (9).

This review aims to assess the potential of insect derived chitosan as a suitable alternative to conventional pesticides for pest and disease management in agriculture. It covers the sources, physiochemical characteristics formulation strategies and mechanisms of action of insect based chitosan while also comparing its advantages over marine derived counterparts. The review also highlights existing research gaps, regulatory challenges and future opportunities for incorporating insect-derived chitosan into mainstream frameworks.

Various source and general characteristics of chitosan

Chitosan, the N-deacetylated derivative of chitin, is a natural polysaccharide, commonly derived from the exoskeleton of insects and crustaceans (8). It is typically obtained through an alkaline deacetylation process where extracted chitin is treated with a 60 % (w/v) sodium hydroxide (NaOH). This reaction is carried out by stirring the mixture at 80 °C-100 °C for 3-4 hours. After the reaction, the pH of the resulting material is neutralized by washing with deionized distilled water. The chitosan is then dried in an oven at 60 °C-80 °C for 24 hours after which the yield is determined. A summary of various chitin and chitosan sources is presented in the Table 1. Chitosan's molecular weight (MW) is determined by the number of monomeric units, typically ranging from 20 to 1200 kDa with this broad variation arising from differences in the source of chitin, extraction methods and the degree of deacetylation (29). MW affects chitosan's viscosity and solubility and is commonly measured via viscosimetry although light scattering and HPLC also are used. The degree of deacetylation (DD) reflects the proportion of 2-amino-2-deoxy-D-glucopyranose units. When the percentage of 2-amino-2-deoxy-D glucopyranose units reaches 50 %, the polymer is typically known as chitosan and turns soluble in aqueous acidic environment (30). Both molecular weight (MW) and degree of

Table 1. Various sources of chitosan

Common names	Species	Reference
Crustaceans		
Crab	*Chionoecetes opilio*	(10)
	Podophthalmus vigil	(11)
	Paralithodes amtschaticus	(12)
	Carcinus mediterraneus	(13)
Water lobster	Crayfish	(14)
Prawn	*Aristens antennatus*	(15)
	Daphnia longispina	
	Anax imperator	
Krill	*Hydrophilus piceus*	(16)
	Notonecta glauca	
	Asellus aquaticus	
Mollusca	*Loliga sp*	(17)
	Todarodes pacificus	(18)
Arthropods		
Spiders	*Geolycosa vultuosa*	(19)
	Hogna radiate	
	Nephila edulis	(20)
Scorpionxs	*Mesobuthus gibbosus*	(21)
Beetles	*Bombyx mori*	(22)
	Holoteichia parallela	(22)
Cockroaches		(23)
Brachiopods		
	Lingual seta	(24)
Fungi		
Ascomydes	*Mucom rouxii*	(25)
Blastomycota	*Blastocladiaceae*	(26)
Chytridiomycota	*Chytridiaceae*	(27)
Protista	Brown algae	(28)
Planta	Green algae	

deacetylation (DD) significantly influence chitosan's functional properties. For example, low-MW chitosan (<100 kDa) with a high DD (>80 %) exhibits better solubility and higher antimicrobial activity while high-MW chitosan (>500 kDa) with moderate DD (60 %-70 %) provides stronger film-forming ability and higher viscosity. Chitosan's crystallinity is often evaluated using the crystallinity index (CI) through X-ray diffraction. As a semi-crystalline biopolymer with polymorphic behavior, its crystallinity affects key characteristics like swelling, porosity and water retention (31). Surface area and particle size are critical for applications like adsorption and enzyme immobilization. Chitosan is nonporous (surface area <10 m^2/g) and modifications are often required. Surface area is measured by the BET method and particle size via sieving, SEM, or particle analyzers (18). Chitosan is categorized into three types based on MW. Low MW: <150 kDa, Medium MW: 150-700 kDa, High MW: >700 kDa (32). Its MW is influenced by source material and processing conditions. Industrial chitosan is typically 100-1200 kDa while native chitin exceeds 1,000,000 Da. Factors like shear, heat (>280 °C), acidsand EDTA can reduce MW (33). The comparison of chitosan properties based on molecular weight is given in the Table 2.

Insects as a source of chitosan

Recent studies have explored the functional characteristics of chitosan derived from cicada quagmires, silkworms and honeybees by extracting chitin from these sources (44). They stated that because insects reproduce quickly and are quick to grow, chitosan derived from insect sources is readily available. Similarly, the removal of chitosan from the original organism influences its biological activity. For instance, extraction from insects can often be performed under moderate conditions such as demineralization with 1 %-2 % HCl at room temperature and deproteinization with 1 %-2 % NaOH at 60 °C-80 °C. In contrast, marine crustacean shells generally require more rigid conditions such as stronger acid concentrations (3 %-5 % HCl) and harsher alkaline treatments (5 %-10 % NaOH at 90 °C-100 °C) which may

Table 2. Comparison of Chitosan Properties Based on Molecular Weight

Property	Low-Molecular-Weight Chitosan (LMWC)	Medium-Molecular-Weight Chitosan (MMWC)	High-Molecular-Weight Chitosan (HMWC)
Solubility	High solubility in water (low viscosity solutions) (34)	Soluble in weak acids; limited solubility (35)	Poor solubility due to entangled chains and H-bonds (36)
Viscosity	Low viscosity (34)	Moderate viscosity; pseudoplastic behavior (37)	High viscosity; pseudoplastic film behavior (37)
Crystallinity	Less crystalline than HMWC (34)	Not specified	More crystalline due to stronger H-bonds (36)
Thermal Properties	Lower melting point, less thermostable (34)	Not specified	High thermal stability; used in coatings (37)
Mechanical Strength	High tensile strength (34)	Strong, especially in pullulan-GO blends (38)	Excellent mechanical resistance in films (37)
Permeability	Higher permeability (34)	Suitable for films and coatings (37,38)	Not highly permeable (36)
Antioxidant Activity	Active; depends on DD and MW (29)	Strongest antioxidant activity among the three (35)	Weak antioxidant activity (39)
Antimicrobial Activity	Strong; varies with DD and MW (e.g., 92 % DD better than 80 %) (40)	Effective, especially in fruit preservation (35)	Strong against some Gram-negative bacteria (41)
Mucoadhesiveness	Present (42)	Not specified	Used in oral extended-release forms (43)
Toxicity	Controversial; depends on MW and DD (32)	Not specified	Generally low but depends on application (36)
Applications	Medical, food, agriculture (34,42)	Film formation, packaging, fruit preservation (37,35)	Antibacterial coatings, pharmaceutical excipients (43)

reduce the functional properties of the resulting chitosan. The yield of chitosan is more in insects that are useful in various applications, including antimicrobial coatings for food preservation, biodegradable films and packaging, wound healing and drug delivery systems in biomedicine, wastewater treatment through heavy metal adsorption, agricultural uses as a biopesticide and plant growth promoter and as a precursor for nanomaterials in biotechnology (45). For example, chitosan extracted from cicada slough, silkworm chrysalises, mealworms and grasshopper species showed higher water holding capacity (594 %-795 %) and fat binding capacity (275 %-645 %) compared to shrimp shell chitosan. This property is a promising feature for food applications. Additionally, *C. molossus* L. consists of 33 g/100 g of chitin that demonstrates better mechanical properties, including tensile strength (62 MPa) and elongation at break (10.4 %) for the production of a biodegradable film similar to that of commercial medical grade shrimp chitosan film (60). Further, chitin isolated from *Pterophyll abeltrani* showed better antifungal activity against the entomopathogenic fungi *M. anisoplia* by 62 % (46). The percentage yield of chitosan varies significantly among different insect groups, as summarized in Table 3. The chitin content varies considerably among insect species. For instance, *Bombyx mori* contains about 3.1 % chitin, while *Clanis bilineata* (Hawkmoth) shows much higher levels with reported values of 95.8 % (47, 48). In the Colorado potato beetle, the chitin content differs with developmental stage, being 72 % in adults and 67 % in larvae (49). The dung beetle (*Catharsius molossus*) contains around 24 % chitin, whereas *Hydrophilus piceus* exhibits a relatively high content of 74 % (44, 50).

Application of chitosan in Agriculture

In agriculture, chitosan holds significant importance due to its biocompatibility, biodegradability and wide spectrum of biological activity. Various applications of chitosan in agriculture shown in fig. 1. In integrated pest management, chitosan serves as a biocontrol agent for deterring insect pests, enhancing plant resistance and reducing reliance on synthetic pesticide (66). In addition to its insecticidal potential, chitosan exhibits notable antimicrobial, antifungal and antiviral activities, acting both directly against phytopathogens and indirectly by inducing plant defense mechanisms, mainly through systemic acquired resistance (SAR) and in some cases also *via* induced systemic resistance (ISR) (67).

It disturbs microbial membranes, chelates metal ions essential for pathogen metabolism and can interfere with the synthesis of microbial proteins and nucleic acids. These properties make it a versatile tool in managing a broad range of plant pathogens including *Fusarium* spp., *Botrytis cinerea*,

Table 3. Percent yield of chitosan from different group of insects

S.NO	Insect Species	Chitosan (%)	Reference
1	*Bombyx mori*	3.1	(47)
2	*Clanis bilineata* (Hawkmoth)	95.8	(48)
3	Colorado potato beetle	Adult -72 Larvae - 67	(49)
4	Dung beetle, *Catharsius molossus*	24	(44)
5	*Hydrophilus piceus*	74	(50)
6	Mealworm, *Tenebrio molitor*	2.5	(47)
7	*Tenebrio molitor*	Dry -14.48 Wet - 13.07	(51)
8	*Zophobas morio*	Larva - 80.00 Adult - 78.33	(52)
9	*Allomyrina dichotoma*	Larva - 83.37 Pupa - 83.37 Adult - 75.00	(52)
10	*Calliptamus barbarous*	70-75	(53)
11	*Gryllus bimaculatus (A)* *Gryllus bimaculatus (B)* *Gryllus bimaculatus (C)* *Gryllus bimaculatus (D)*	86.44 94.14 90.26 79.03	(54)
12	Grasshopper	5.7	(47)
13	House cricket, *Brachytrupes portentous*	2.4-5.8	(55)
14	Moroccan locust	Nymphs - 77.38 Adults - 81.69	(56)
15	Mexican katydid, *Pterophylla beitrani*	58.8	(46)
16	*Oedaleus decorus*	74-76	(53)
17	*Schistocerca gregaria*	55	(57)
18	*Apis mellifera*	16-25	(58)
19	*Blattella germanica*	Nymphs - 2.6 Adults - 2.8	(59)
20	*Ranatra linearis* (Aquatic bug)	70	(50)
21	*Chrysomya megacephala* (Blowfly)	26.2	(60)
22	*Drosophila melanogaster*	70.91	(61)
23	*Anax imperator* (Emperor dragonfly)	67	(50)
24	*Hermetia illucens*	32	(62)
25	*Musca domestica*	5.87	(63)
26	Cicada slough	28.2	(47)
27	*Periplaneta americana*	2.08 0.024 Nymphs - 4 Adults - 7.4	(64) (65) (59)

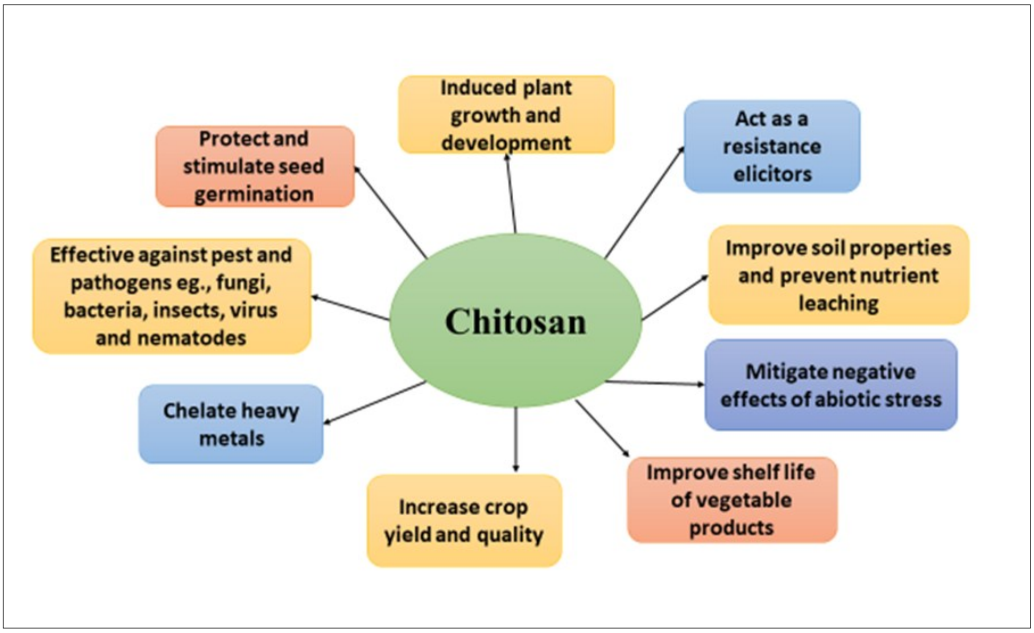

Fig. 1. Various applications of chitosan in the agriculture.

Rhizoctonia solani and various plant viruses. Its antiviral effects have been observed through inhibition of virus replication and systemic movement, particularly against tobacco mosaic virus (TMV) and cucumber mosaic virus (CMV) (68). Due to its multifaceted bioactivity, low toxicity and environmental safety, chitosan is increasingly recognized as a sustainable and effective alternative for managing pests and diseases in modern agriculture.

Chitosan in insect pest management

Chitosan enhances the availability and stability of certain insecticides and botanicals and its derivatives exhibit insecticidal effectiveness against a range of agricultural pests (69). By enriching various formulations of chitosan with inorganic or natural pesticide have been studied as approaches for protection of food as well as agricultural and public health insect pest control.

The chitosan polymer has been incorporated into diverse formulations. These include: (i) coatings, such as ordinary chitosan, chitosan combined with essential oils and chitosan-based active packaging; (ii) chitosan oligosaccharides and (iii) nanoparticle-based systems including chitosan nanoparticles loaded with essential oils or agrochemicals, chitosan-poly (acrylic acid) nanoparticles, myristic acid-chitosan nanoparticles and chitosan nanoparticles for RNAi delivery as shown in Table 4 (70). Chitosan film incorporated with citronella essential oil (2 %), polyethylene glycol (PEG) and carboxymethyl cellulose (CMC) applied on guava fruit effectively reduced oviposition of *Bactrocera carambolae* by 85 % compared to the control. Similarly, cardboard coated with chitosan and lemongrass essential oil exhibited 100 % insecticidal toxicity against *Sitophilus zeamais* after 360 hours while also improving barrier properties, air permeability and biodegradability. Chitosan has shown significant insecticidal activity, attributed mainly to its antimicrobial effects which disrupt the gut microbiota of insect pests. In laboratory bioassays, a 2 % chitosan solution in artificial diet reduced the survival period of house flies, horse flies and blowflies drastically from their usual 13-24 days down to just 4-6 days. This has been linked to physiological and structural changes in the midgut of insects though the exact mode of action is still being studied. Chitosan nanoparticles loaded with essential oils (EOs) such as *Lippia sidoides* and *Siparuna guianensis* have demonstrated high larvicidal activity against disease vectors like *Aedes aegypti*. For instance, one formulation achieved 100 % mortality in mosquito larvae at low concentrations within two days while also maintaining efficacy at lower doses over extended periods. These nano-formulations can induce repellence or even attract specific pests offering potential in trap development. Chitosan acts as a plant defense stimulant with seed coatings and foliar sprays boosting plant resistance, reducing insect oviposition and limiting larval development. Studies have found notable mortality rates in pests like *Helicoverpa armegira, Plutella xylostella* and aphids and protective effects against storage pests when used in seed treatments. For *Spodoptera litura* larvae, a chitosan bioassay resulted in up to 62 % mortality within seven days after treatment.

Antimicrobial activity of chitosan

The antimicrobial efficacy of chitosan is influenced by several factors, including the type of microorganism, degree of deacetylation (DD), molecular weight (MW), chitosan concentration, temperature, pH and the culture medium (103). Chitosan has shown the ability to suppress soil born disease like *Fusarium* wilts, controlling fungal growth, enhancing plant defense responses and stimulating beneficial soil microorganisms (104). Microorganisms affected by chitosan can generally be categorized as fungi exhibiting varying either sensitive level and it also acts on both Gram-positive and Gram-negative bacteria (105). Among the bacterial species that chitosan can inhibit is *Xanthomonas campestris pv. campestris* (Xcc) which causes black rot in cruciferous crops. Chitosan, especially when loaded with thymol in nanoparticle form, significantly inhibits Xcc growth by damaging bacterial membranes, disrupting biofilm formation and reducing production of virulence factors. This creates cellular damage and kills Xcc bacteria effectively, *Pseudomonas syringae* a known plant pathogen targeted by chitosan's antimicrobial action, *Agrobacterium tumefaciens*, a causative agent of crown gall disease in plants, is inhibited by chitosan (106). Studies show chitosan products of varying molecular weights have antibacterial effects, with lower-weight chitosan often more effective and *Erwinia carotovora,* responsible for soft rot in various plants, is also susceptible to inhibition by chitosan (107). However, research suggests that chitosan tends to be more effective in controlling fungal pathogens than bacterial ones, likely due to differences in cell wall composition as fungal cell walls are rich

Table 4. Chitosan and its derivatives in insect pest management

Target Species	Chitosan Application Method	Concentration	Observed Effect	Reference
Pure chitosan				
Musca domestica (housefly)	Incorporated in artificial diet	2 %	Survival reduced from 13 to 4 days	(71)
Tabanus nigrovittatus	Incorporated in artificial diet	2 %	Survival reduced from 16 to 4.5 days	
Phormia regina	Incorporated in artificial diet	2 %	Survival reduced from 24 to 6 days	
Unspecified termite species	Chitosan-treated milled paper	Not specified	Increased mortality (80 %) compared to control (45 %) due to feeding disruption	(72)
Reticulitermes flavipes	Chitosan-treated wood	2 %	>94 % mortality after 28 days	(73)
Reticulitermes virginicus	Chitosan-treated wood	0.5 %	>90 % mortality at lowest concentration	
Reticulitermes virginicus	Chitosan-treated wood (protist diversity test)	Not specified	Protist species reduced from 10 (control) to 2 (treated) in termite hindgut	(74)
Coated chitosan				
Anastrepha ludens (Mexican fruit fly)	Chitosan coating on mango fruit	Not specified	Inhibited egg and larval development; slowed ripening; reduced fruit weight; increased phenolics and gas exchange	(75)
Anastrepha obliqua	Chitosan coating on mango fruit	Not specified	Inhibited egg and larval development; slowed ripening; reduced fruit weight; increased phenolics and gas exchange	(76)
Chitosan Coating with Essential Oils				
Bactrocera carambolae	Chitosan film with citronella EO, PEG and CMC on guava fruit	2 % citronella EO	85 % reduction in oviposition compared to control	(77)
Plutella xylostella	Chitosan coating enriched with jasmonic acid on cabbage seeds	Not specified	57 % preimaginal mortality; inhibited adult emergence	(78)
Myzus persicae	Chitosan coating enriched with jasmonic acid on cabbage seeds	Not specified	57 % preimaginal mortality; inhibited adult emergence	(78)
Acanthoscelides obtectus	Chitosan film with *Ferulago campestris* EO on bean seeds	57.7 µL/L of air (highest concentration tested)	93.3 % repellency; no negative effects on bean growth; suppressed weed seed germination *in vitro*	(79)
Calliphora vomitoria	Chitosan coating on meat with *L. nobilis* and *P. nigrum* EOs	1 % chitosan + 0.1 % EO	Reduced oviposition by 84.9 % (*L. nobilis*) and 93.3 % (*P. nigrum*); delayed meat desiccation and lipid peroxidation	(80)
Sitophilus oryzae	Chitosan coating on rice with eucalyptus and tea tree EOs + gamma radiation	0.2 µL/mL EO; gamma radiation at 100 -300 Gy	100 % mortality within 24-48h; full protection with gamma radiation for up to 14 days	(81)
Chitosan Coating in Active Packaging				
Sitophilus zeamais (maize weevil)	Coating of cardboard with chitosan and lemongrass essential oil	Not specified	100 % insecticidal toxicity after 360 hr; improved barrier properties, air permeability and biodegradability	(82)

Chitosan and Nematodes

Target Pest	Host Plant	EPN Species	Treatment Condition	Observed Effect	Reference
Rhynchophorus ferrugineus	*Phoenix canariensis*	*Steinernema carpocapsae*	Lab & Field	Chitosan enhances EPN efficacy	(83)
R. ferrugineus (larvae)		*S. carpocapsae* + Chitosan	Curative assay - 28 days	81.3 % larval mortality	(84)
R. ferrugineus (immature stages)			15 days post-treatment	98.2 % mortality	(83)
R. ferrugineus (immature)		*S. carpocapsae* + Chitosan formulation	-	99.7 % mortality	(83)

Chitosan derivatives

Insecticidal Activity of Chitosan Oligosaccharide

Target Pest	Application Method	Insecticidal Effect	Time Frame	Reference
Helicoverpa armigera	Foliar spray	40 % mortality	72 hr	(85)
Plutella xylostella	Foliar spray	70 % mortality	72 hr	
Hyalopterus pruni	Foliar spray	93 % mortality	Not specified	
Rhopalosiphum padi, *Sitobion avenae*, *Metopolophium dirhodum*, *Myzus persicae*, *Aphis gossypii*	Foliar spray	Effective control (qualitative)	Not specified	

Insecticidal Effects of Functional Group-Modified Chitosan Derivatives

Target Insect	Chitosan Derivative	Observed Effect/ Duration	Reference
Spodoptera littoralis	N-(2-chloro-6-fluorobenzyl) chitosan	LC_{50} = 0.32 g/kg; LC_{100} = 0.625 g/kg diet	(86)
	N-(Propyl) chitosan	76 % larval weight reduction; After 4 days	(87)
	N-(Undecanyl) chitosan	66 % larval weight reduction; After 4 days	
	N-(Phenyl propyl) chitosan	65 % larval weight reduction; After 4 days	
	O-(Decanyl) chitosan	64 % larval weight reduction; After 4 days	(88)

Insecticidal Efficacy of Chitosan-Metal Complexes

Target Insect	Chitosan Formulation with Molecular Weight (g/mol)	Observed Effect	Reference
Spodoptera littoralis	Chitosan alone ; 2.27×10^5	50 % larval mortality (artificial diet)	(89)
	Chitosan-Ni complex	93 % larval mortality	
	Chitosan-Hg complex	83 % larval mortality	
Aphis nerii	Chitosan (various MWs) 2.27×10^5, 3.60×10^5, 5.97×10^5	96 %, 87 % and 100 % mortality respectively	
	Chitosan-Cu complex	94 % mortality (most effective metal complex)	

Chitosan Nano particles

CNPs Loaded with Essential Oils

Target Insect	Essential Oil (EO)	LC_{50} (µL/L air)	Mortality/Protection	Reference (s)
Sitophilus oryzae	*Piper nigrum* EO	25.03	0 % grain damage vs. 74 % in control	(90)
Tribolium castaneum		29.02	0 % grain damage vs. 86 % in control	
S. oryzae	Peppermint EO	28.61	Higher toxicity than control (56.48 µL/L)	
T. castaneum		34.79	Higher toxicity than control (62.94 µL/L)	
T. castaneum	*Melissa officinalis* EO	0.048 µL/mL air	Higher than control (0.071 µL/mL air)	(91)
Oryzaephilus surinamensis	Rosemary EO	Not stated	82 % mortality (vs. 62 % untreated)	(92)
Carpophilus hemipterus		Not stated	50.7 % mortality (vs. 19 % untreated)	(93)
Anopheles stephensi	*Elettaria cardamomum*	7.58 µg/mL	Significant larvicidal activity after 24 hr	(94)
Anopheles stephensi	*Cinnamomum zeylanicum*	2.98 µg/mL	Similar significant larvicidal activity	(94)
Culex pipiens	*Geranium maculatum*	22.63 ppm	Larvicidal effect after 5 days	(95)
Culex pipiens	*Citrus bergamia*	38.52 ppm	High larvicidal activity after 3 days	
Aedes aegypti	*Lippia sidoides*	Not stated	85 % mortality (24 hr), 92 % (48-72 hr)	

Insect Behaviour Modulation & Attraction

Bemisia tabaci	Geraniol-loaded CNP	Stable attractant effect	60 days	(96)
	Stylosanthes guianensis EO	High toxicity with 6.67 mg/mL CNP		

Botanical Extracts or Biopesticides

Target Insect	Formulation	Observed Effect	Reference
Musca domestica	CNP + *Nerium oleander* leaf extract	LC_{50} = 0.64 ppm; 27 % pupation, 60 % adult emergence reduction after 48 hr	(97)
Helicoverpa armigera	Chitosan-TPP-Poineem (neem, karanja oils, etc.)	88.5 % antifeedant; 90.2 % larvicidal activity	(69)
H. armigera	Chitosan-GLA-Poineem	72.3 % antifeedant; 87.5 % larvicidal activity	(69)
Spodoptera litura	CNP + metabolites from *Nomuraea rileyi*	99 % larvicidal activity on 4th instar larvae	(90)

Synthetic Insecticides & Polymers

Aphis gossypii	Chitosan-g-polyacrylic acid NPs (castor leaves)	77.8 % growth inhibition, 75 % reduction in adult emergence	(98)
Cassida vittata	Nanochitosan-g-polyacrylic acid	Egg oviposition dropped from 266 to 3 eggs; 100 % egg, 91 % larval mortality	(99)
Sitophilus granarius	MA-CNP + *Cuminum cyminum* EO	100 % mortality within 48 hr; 50 % mortality after 12 days	(100)
S. granarius	MA-CNP + *Carum copticum* EO	89 % mortality (48 hr); 20 % (12 days)	(101)
Tribolium confusum	MA-CNP + *Cuminum cyminum* EO	100 % mortality within 48 hr; 50 % after 24 days	(100)
T. confusum	MA-CNP + *Carum copticum* EO	80 % mortality (48 hr); 40 % (24 days)	(101)

RNA Interference (RNAi) for Vector Control

Target Species	Formulation	Mode of Action/ Effect	Reference
Anopheles gambiae	CNP + dsRNA/siRNA	Gene silencing via oral ingestion; Impaired mobility & metabolism	(102)
Aedes aegypti	CNP + dsRNA/siRNA	Gene knockdown targeting larval development; Effective vector control tool	

Table 5. Antimicrobial, Antifungal and Antiviral activity of chitosan

Antimicrobial Activity of chitosan			
Microorganism	**Susceptible to**	**Observed Effects / Findings**	**Reference**
Rhizopus stolonifer	LMWC	Strong inhibition observed; LMWC was most effective against this fungus.	(108)
Pseudomonas syringae pv. *tomato*	LMWC (78 % DD, 70 kDa MW)	No resistance observed; LMWC significantly effective.	(106)
Erwinia carotovora	LMWC	Significantly inhibited by LMWC; enhanced with citral synergy.	(109,110)
Agrobacterium tumefaciens	LMWC	Growth suppressed by LMWC.	(109)
Pseudomonas aeruginosa, *P. oleovorans*	LMWC > HMWC	LMWC showed 72.52 % inhibition; HMWC showed 64.57 %.	(111)
Aspergillus niger	LMWC + citral	Combined effect showed notable inhibition.	(110)
Xanthomonas gardneri	MMWC	Inhibited tomato infection; MMWC suppressed disease symptoms.	(112)
Staphylococcus aureus	MMWC and HMWC	MMWC effective against multiresistant strains; HMWC formed thick polymer barrier and degraded cell membrane.	(113)
Lactobacillus casei	MMWC	MMWC exhibited antimicrobial activity.	(113)
Escherichia coli	LMWC and HMWC	LMWC effective due to high solubility; HMWC caused rupture via cationic binding.	(113)
Alternaria solani	HMWC	HMWC showed high efficacy in suppressing fungal growth.	(108)
Fusarium oxysporum f. sp. *vasinfectum*	HMWC	HMWC proved highly effective in pathogen suppression.	(108)
Antifungal activity of chitosan			
Fungal Species	**Chitosan Type**	**Observed Antifungal Effect**	**Reference**
Colletotrichum gloeosporioides	LMWC	Inhibited mycelial growth *in vitro* and in dragon fruit.	(7)
Alternaria alternata	LMWC	*In vitro* suppression; interfered with spore viability and mycelial development.	(7)
Rhizopus stolonifer	LMWC, MMWC, HMWC	Strong inhibition observed; HMWC produced variable spore morphology.	(7)
Botrytis cinerea	LMWC, MMWC, HMWC	Mycelial growth reduced; best inhibition at lower MW; synergistic with fungicides.	(115)
Aspergillus niger	LMWC	Most effective at low MW; reduced fungal development.	(118)
Penicillium digitatum	LMWC, HMWC	Successfully controlled citrus green mold; reduced postharvest decay.	(4)
Penicillium expansum	LMWC	Mycelial growth significantly inhibited.	(118)
Aspergillus ochraceus	LMWC	Inhibited spore germination and altered microstructure and morphology.	(119)
Fusarium oxysporum	LMWC, MMWC, HMWC	Broadly suppressed growth across all MW types; best effects with MMWC & HMWC.	(109)
Pythium debaryanum	LMWC	Growth inhibited.	(106)
Fusarium eumartii	LMWC	Spores suppressed.	(120)
Fusarium moniliforme	LMWC	Protection observed in maize seedlings under abiotic stress.	(121)
Fusarium graminearum	LMWC, MMWC	Mycotoxin production and vegetative growth reduced.	(122)
Rhizoctonia solani	LMWC, MMWC	Inhibited in rice and *in vitro*; spore protein release increased with MW.	(117)
Ceratocystis fimbriata	MMWC (300 kDa)	Reduced spore germination and hyphal growth in sweet potato.	(123)
Sclerotinia sclerotiorum	MMWC (350 kDa, 90 % DD)	Growth suppression and induced defense in carrot.	(124)
Fusarium spp.	MMWC (150 kDa)	Wilt intensity reduced in treated potato plants.	(125)
Lasiodiplodia spp.	HMWC (with *azoxystrobin, isopyrazam*)	Prevented leaf spot in kiwifruit.	(126)
Antiviral activity of chitosan			
Virus	**Effective Chitosan Type**	**Observed Effects**	**Reference**
Tobacco Mosaic Virus (TMV)	LMWC	LMWC reduced localized necrosis in tobacco by 50 %-90 %. Also decreased TMV infection levels when applied to roots or leaves.	(133)
Meloidogyne incognita(root-knot nematode)	LMWC	LMWC (oligo-chitosan) effectively suppressed TMV infection and nematode infestation in tobacco plants.	(133)
Alfalfa Mosaic Virus (AMV)	LMWC	Resistance developed in untreated parts of bean leaves after LMWC was applied to the lower surface.	(134)
Bean Mild Mosaic Virus (BMMV)	LMWC	Pathogen showed increased resistance to chitosan as MW decreased.	(109)
Pepper Mild Mottle Virus (PMMoV)	MMWC (600 kDa)	Foliar spray activated defense genes in chili plants and prevented virus accumulation.	(135)
Cucumber Mosaic Virus (CMV)	MMWC (600 kDa)	Virus levels were reduced in plants after MMWC foliar application.	(135)
Bursaphelenchus xylophilus(Pine Wood Nematode)	HMWC > LMWC	HMWC more effective than LMWC in reducing nematode-related disease severity.	(136)
Tobacco Mosaic Virus (TMV)	HMWC (enzymatically degraded)	Local necrotic lesions on tobacco leaves were suppressed after treatment with HMWC broken down by *Aspergillus fumigatus* chitinase.	(137)
Unknown Gall-Forming Agent*(likely nematode-associated)*	LMWC (90 %), HMWC (93 %)	Significant reduction in gall formation with both LMWC and HMWC (1:1 dilution).	(138)

in chitin and glucans that interact strongly with chitosan (Table 5).

Antifungal activity of chitosan

Chitosan exhibits potent antifungal activity by targeting multiple stages of fungal development through several mechanisms. Its polycationic nature allows it to interact strongly with the negatively charged components of fungal cell membranes, leading to increased membrane permeability and disruption. This causes leakage of essential intracellular contents, ultimately damaging the cell surface and weakening fungal cells. Chitosan also interferes with spore germination and hyphal growth by disrupting membrane integrity and cell wall formation, which are critical for fungal development and pathogenicity. Additionally, it chelates essential nutrients like metal ions, depriving fungi of vital elements necessary for their metabolism and survival. At the molecular level, chitosan inhibits the expression of genes related to cell wall integrity and function, such as those in the SAGA complex, further compromising fungal cell surface structure and defense. It also induces oxidative stress within fungal cells by increasing reactive oxygen species, damaging cellular components and suppressing sporulation and spore viability. These multifaceted actions collectively enable chitosan to effectively suppress the growth and spread of harmful fungi such as *Colletotrichum gloeosporioides*, *Alternaria alternata*, *Rhizopus stolonifer* and *Botrytis cinerea*, making it a promising natural antifungal agent for plant protection (7). Its antifungal efficacy extends beyond laboratory conditions and also shows significant antifungal performance in living plants. For instance, it has been successfully applied to control *Physalophora piricola* and *Alternaria kikuchiana* in pears. Both chitosan and oligochitosan strongly inhibit spore germination and mycelial growth of *Alternaria kikuchiana* and *Physalospora piricola*. Their inhibitory effects on mycelial growth are more pronounced than on spore germination and this inhibition is concentration dependent. At 5.0 g/L, both compounds completely inhibited the mycelial growth of the fungi, Chitosan coatings and conjugates with Streptomyces bioactives effectively control *Botrytis cinerea* in grapes and strawberries by inhibiting fungal growth, delaying gray mold and preserving fruit quality (114). They enhance firmness, reduce respiration, boost phenolic content and peroxidase activity, while acting through membrane disruption, cell wall damage, oxidative stress and activation of plant defenses (115). Regarding *Colletotrichum gloeosporioides* in dragon fruit, specific findings were not detailed in the retrieved documents but this pathogen is commonly targeted by similar natural fungicidal approaches including chitosan treatments (116). In rice, its antifungal impact against *Rhizoctonia solani* was confirmed through pathogenicity assays and transmission electron microscopy observations (117).

Antiviral activity of chitosan

Chitosan also shows promising antiviral activity, particularly by inducing resistance against systemic plant viruses which are often difficult to control. Numerous studies have documented the ability of chitosan to trigger antiviral resistance in plants. Chitosan applied by spraying or inoculation of leaves protected various plant species against local and systemic infections caused by alfalfa mosaic virus (ALMV) (127). Systemic plant viruses tend to cause more severe damage, making their control a priority. Among the available strategies, applying chitosan as an antiviral agent has been shown to be effective ways to reduce viral infections (128). Treating potato plants infected with Potato Virus X (PVX) led to enhanced resistance against the virus. Likewise, chitosan-treated tomato plants not only exhibited resistance to Tomato Mosaic Virus but also showed improved vegetative growth (129). When applied in combination with plant growth-promoting rhizobacteria (PGPR), chitosan also helped tomato plants resist Leaf Curl Virus. The combined application of *Pseudomonas* spp. (206(4) + B - 15 + JK - 16) with chitosan significantly improved tomato plant resistance to Leaf Curl Virus with up to 100 % disease severity reduction, improved growth and defense responses and lowered viral load and vector populations under field conditions (130). For Squash Mosaic Virus (SMV), studies cited showed that chitosan had promising antiviral activity, but specific application rates for SMV were not detailed in the searched references (128). However, general antiviral chitosan applications reported include foliar spray treatments ranging from 0.001 % to 0.1 % chitosan solutions applied before inoculation which resulted in significant virus resistance and reduction in viral infection in various plants (131). The specific characteristics within the host plant may play a role in initiating antiviral defenses following chitosan application. Supporting this, chitosan oligosaccharides have been shown to activate the salicylic acid signaling pathway, thereby inducing resistance to Tobacco Mosaic Virus (TMV) (132). The various antiviral applications of chitosan are summarized in Table 5.

Effects of chitosan on various applications on crops

It has emerged as a potent bio-stimulant and stress alleviator in plants exposed to various abiotic stress such as drought, salinity, extreme temperatures and heavy metals toxicity due to its biodegradable, non-toxic and biocompatible nature (139). It is also being extensively explored in sustainable agriculture as a plant protection and enhancement agent under adverse environmental conditions. Chitosan also positively influence seed germination, root elongation, shoot development and nutrient assimilation by modulating plant hormones and enhancing physiological activity (140). Application of chitosan improves root and shoot length in vegetable crops like tomato and cucumber as well as it enhances chlorophyll content and photosynthetic rate by improving nitrogen assimilation (141). In yield enhancement, it improves flowering, fruit set and crop productivity, especially in fruit and vegetable crops. It influences reproductive physiology and improves the nutritional profile of produce. The foliar spray of chitosan (0.2 %) increased the number of fruits per plant, average weight and total yield on tomato and chilli (142). Chitosan increases activities of peroxidase (POD), catalase (CAT) and Phenylalanine ammonia-lyase (PAL), improving plant defense. Chitosan modulates auxin, cytokinin and abscisic acid levels, influencing stomatal behavior and water conversion (143). Chitosan based edible coating are widely applied to fruits and vegetable to extend shelf life, reduce microbial contamination and preserve quality during storage. In strawberries and tomatoes, chitosan coating extended shelf life by 5-7 days while preserving firmness and ascorbic acid levels (144). It also inhibits fungal growth such as *Botrytis cinerea* and *Penicillium* spp., reducing decay (145). The various effects of chitosan are summarized in the Table 6.

Challenges and limitations

While insects have emerged as a promising alternative to marine organisms for chitosan extraction, several technical and biological challenges limit their large-scale utilization. The interspecies variability in chitin content influenced by insect species, developmental stages and rearing substrates, complicates the standardization of extraction

Table 6. Various effects of chitosan in crop

Plant Species	Observed Effect of Chitosan	Reference No.
Effects on Abiotic stress		
Drought stress		
Apple (*Malus domestica*)	Increased antioxidant activity, reduced electrolyte leakage, improved moisture retention	(146)
Potato (*Solanum tuberosum*)	Enhanced drought tolerance via antioxidant enzyme activation	(147)
Moth orchid (*Phalaenopsis spp.*)	Stimulated endogenous chitosan and antioxidant activity	(148)
Rice (*Oryza sativa*)	Promoted drought resistance via root development and H_2O_2 signaling	(149)
White clover (*Trifolium repens*)	Increased root growth and drought tolerance	(150)
Grapevine (*Vitis vinifera*)	Strengthened antioxidant defenses under water deficit	(151)
General (multiple species)	Induced abscisic acid (ABA) activity leading to reduced transpiration through stomatal regulation	(152)
Heat stress		
Dry bean (*Phaseolus vulgaris*)	Helped mitigate heat stress effects in late-sown crops	(153)
General	ABA induction by chitosan may stimulate heat-stress responsive (HS) gene expression	(154)
General	Overexpression of ABF3 (ABA-responsive gene) confers heat tolerance; chitosan may promote this pathway	(155)
Effects on plant growth, yield and physiology		
Mango (*Mangifera indica*)	Foliar spray (5 mL L^{-1}) increased fruit number/tree, size, weight and vegetative growth	(156)
Kiwi (*Actinidia deliciosa*)	Spraying improved fresh fruit weight under field conditions	(157)
Peach (*Prunus persica*)	Chitosan + calcium chloride reduced early swelling, enhanced firmness, reduced weight loss	(158)
Nectarine (*Prunus persica* var. *nucipersica*)	Improved soluble solids and maintained post-harvest firmness	(159)
Tomato (*Solanum lycopersicum*)	Increased phenolics, PPO, phytoalexins, fruit weight and yield	(160)
Grapevine (*Vitis vinifera*)	Boosted vegetative development and physiology	(161)
Dendrobium orchids (*Dendrobium spp.*)	Stimulated growth and productivity	(162)
Cabbage (*Brassica oleracea*)	Chitosan-treated plants outperformed controls in growth	(163)
Cucumber (*Cucumis sativus*)	Alleviated cold stress, reduced ROS, improved photosynthesis, strengthened membranes	(164)
Chili (*Capsicum annuum*)	Improved seed germination, vigor, quality, aging resistance and storage life	(165)
Post-harvest effects		
Mangifera indica	Reduced tissue rot, increased ascorbic acid, extended shelf life, maintained freshness	(166)
Punica granatum	Enhanced shelf life (up to 16 days), improved freshness, suppressed microbial growth	(167)
Prunus avium	Increased anthocyanins, delayed color change, maintained water content	(168)
Fragaria × ananassa	Prolonged anthocyanin and antioxidant activity, reduced browning	(169)
Syzygium samarangense	Decreased disease severity, maintained firmness, reduced weight loss	(170)
Prunus armeniaca	Enhanced antioxidant enzymes, increased total phenolic content	(171)
Musa spp.	Delayed ripening, improved shelf life, increased vitamin C and antioxidant activity	(172)
Citrus spp.	Controlled green mold, maintained firmness, color, juice quality	(173)
Solanum lycopersicum	Enhanced shelf life and appearance during refrigeration	(174)
Daucus carota	Delayed ripening, reduced sugar, increased total phenolics	(175)
Brassica oleracea var. italica	Combined with mild heat: improved shelf life, maintained sensory quality	(176)
Cucumis sativus	Induced chilling tolerance, preserved quality, enhanced shelf life	(177)
Cucumis melo	Extended shelf life, improved antioxidants and quality retention	(178)

protocols and quality assessment. Additionally, chitin in insects is bound with sclerotized proteins and melanin pigments especially in adult stages, making deproteinization and decolorization more complex than in crustaceans. Moreover, the lack of optimized and universally accepted extraction procedures for insect-derived chitosan, especially for non-model species leads to inconsistent physicochemical properties (e.g. degree of deacetylation, molecular weight) which are critical for biological activity and formulation efficiency (179). Current extraction methods are also associated with high production costs, energy-intensive chemical treatments and environmental concerns due to the use of acids and alkalis, limiting their scalability and sustainability.

Despite significant evidence supporting the antimicrobial and pesticide potential of chitosan and there are certain limitations in the field level application. Chitosan-based formulations can degrade under UV light, extreme pH and microbial activity which reduces their shelf life and efficacy in open-field applications. Despite this, they induce systemic resistance in plants and affect a broad spectrum of pathogens and insects (180). Its non - specific mode of action may be less effective compared to targeted synthetic pesticides in some cases. The elicitors of chitosan are influenced by crop species, developmental stage and environmental condition. The efficacy variation is common field to field. The solubility and pH of the pure chitosan are very low. Hence the nano-formulation and chemical modification of the chitosan have improved the solubility and delivery, their cost, regulatory barriers and ecological impact are still under study (181).

Future Perspectives

To address the existing challenges and unlock the full potential of insect-derived chitosan in agriculture, several key research directions must be prioritized. First, standardizing extraction methods across insect species, optimizing yield and preserving functional properties while reducing chemical inputs. Genetic and metabolic studies to identify insect strains with naturally high chitin content or engineered biosynthesis pathways for enhanced biopolymer production. Development of green and enzymatic extraction methods to replace harsh chemical treatments, enhancing environmental sustainability and product purity. Design of smart delivery systems (e.g. pH-responsive, UV-stable chitosan nanoparticles) to increase efficacy and durability under diverse field conditions. Multi-omics approaches (transcriptomics, proteomics) to understand the mechanisms of plant defense activation by insect-derived chitosan, helping in formulation optimization. Toxicological and environmental safety studies to evaluate the long-term impact of insect chitosan and its nano formulations on soil microbiota, non-target organisms and crop residues. Exploration of synergistic combinations with beneficial microbes, biocontrol agents and plant growth promoters to enhance integrated pest and disease management systems. As the bioeconomy advances, insect farming integrated with waste valorization and chitosan recovery can contribute significantly to sustainable agriculture, circular economy and green pest management. Collaborative efforts among academia, industry and regulatory agencies will be pivotal in translating laboratory findings into scalable field applications.

Conclusion

The increasing global emphasis on sustainable agriculture and minimizing the use of synthetic pesticides has highlighted chitosan as a promising natural biopolymer for integrated pest and disease management. Although crustaceans have been the conventional source of chitosan, recent interest in insects as an alternative origin has gained momentum due to their environmental sustainability and economic viability. Species such as black soldier fly, mealworm and silkworm pupae have shown considerable potential for efficient chitin recovery, offering desirable physicochemical characteristics and bioactivity for agricultural applications. In agriculture, the chitosan serves multiple functions, acting as an antimicrobial agent, an inducer of plant defense mechanisms, a growth promoter and a biopesticide. Its adaptability to various formulations such as foliar sprays, seed coating and nanoparticle-based systems broaden its utility in crop protection strategies. Nonetheless, despite these promising attributes, the large-scale implementation of insect sourced chitosan remains constrained by technical hurdles, regulatory uncertainties and limited market development. To harness the full potential of this biopolymer, future research must focus on standardizing insect chitosan production methods, improving formulation stability and conducting long term field trails. Additionally, interdisciplinary collaborations involving entomologist, chemists, agronomists and policymakers are essential to address regulatory gaps, safety assessment and scalable commercialization. Overall, insect-derived chitosan represents a viable, eco-friendly solution for modern agricultural challenges, aligning well with the principles of sustainable development, waste valorization and circular bioeconomy. With continued research and policy support, it holds strong potential to transform pest and disease management practices in a greener and more resilient agricultural future.

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Authors' contributions

AA contributed to conceptualization, literature search, data collection and visualization and prepared the original draft. SG, SM and MM were involved in literature review, data analysis and review and editing of the manuscript. AR provided methodology support, critical revisions and supervision. SS and SA contributed to visualization, reference management and formatting. All authors read and approved the final manuscript.

Compliance with ethical standards

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