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Chitosan: The optimal solution for sustainable plant disease management in agriculture

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Abstract

Chitosan, a natural polymer derived from chitin, has gained prominence as a sustainable solution for plant disease management in agriculture. Its unique properties, including biodegradability, biocompatibility, and antimicrobial activity, make it an ideal alternative to chemical pesticides. This review explores the mechanisms by which chitosan enhances plant defense, including its role as an elicitor of plant immune responses and its direct antimicrobial effects on pathogens. Recent studies highlight its applications in seed coating, foliar sprays, soil amendments, and post-harvest treatments. The environmental and economic benefits of chitosan, as well as the challenges and future prospects for its use, are also discussed. As research advances, chitosan is poised to play a crucial role in sustainable agriculture, offering eco-friendly and effective disease management solutions that reduce reliance on synthetic chemicals.

Keywords: Chitosan, plant diseases, antimicrobial activity, sustainable, management

Introduction

In the face of a rapidly growing global population and escalating environmental concerns, agriculture is increasingly turning to sustainable practices to meet food production demands while mitigating negative ecological impacts. One such promising approach is the use of chitosan, a biopolymer derived from chitin, the structural material found in the shells of crustaceans like shrimp and crabs (Hudson *et al.*, 2011) [23]. Chitosan's unique properties, including its biodegradability, non-toxicity, and antimicrobial activity, position it as a valuable alternative to traditional synthetic pesticides. Historically, chitosan has been utilized in various fields due to its biocompatibility and environmental friendliness. In agriculture, its potential as a plant disease management tool has garnered significant interest. When applied to plants, chitosan acts as an elicitor, stimulating the plant's innate immune response. This enhanced defense mechanism involves the production of defense-related compounds such as phytoalexins and pathogenesis-related proteins, which help plants fend off pathogens. Additionally, chitosan exhibits direct antimicrobial properties, effectively inhibiting the growth of a wide range of plant pathogens including fungi, bacteria, and viruses (Ke *et al.*, 2021 Chakraborty *et al.*, 2020) [27, 10]. The application of chitosan in agriculture extends beyond disease management. It is employed in seed coatings to boost germination rates and protect seedlings from soil-borne pathogens. Chitosan is also used as a foliar spray to form a protective barrier on plant surfaces, reducing the incidence of infections and improving overall plant health. Furthermore, its role in post-harvest treatments helps extend

the shelf life of fruits and vegetables by preventing microbial spoilage. Recent research has highlighted chitosan's effectiveness in various agricultural settings, demonstrating its ability to enhance crop yield and quality while reducing reliance on chemical pesticides. Despite its benefits, the widespread adoption of chitosan faces challenges such as varying efficacy under different conditions and the need for optimized formulations. As research continues, chitosan holds the promise of advancing sustainable agricultural practices, offering a viable solution to the pressing issue of plant disease management.

Chitosan chemical, physical, and biological features

Chitosan has garnered significant attention from researchers over the past two decades due to its diverse properties and potential applications across various scientific and practical fields. Several critical factors influence the properties of chitosan, including its molecular weight, degree of deacetylation, and solubility. The molecular weight of chitosan can range from 50 to 2000 kDa, depending on the source of chitin. This range affects the crystal size and morphological characteristics of chitosan-based thin-film composites (TFCs) and other products or membranes. The molecular weight of chitosan also influences the viscoelastic properties of its solutions and hydrated colloidal forms. The degree of deacetylation, which indicates the extent to which chitin has been converted to chitosan, affects the concentration of free -NH₂ groups in the polysaccharide. This, in turn, impacts all of chitosan's functional properties. Chitosan dissolves more readily in acidic media compared to neutral or basic conditions, with its solubility influenced

by factors such as polymer molecular weight, degree of acetylation, pH, temperature, and crystallinity (Wang *et al.*, 2005) ^[53]. Chemically, chitosan is characterized by its linear polyamine structure, reactive amino and hydroxyl groups, and ability to chelate metal ions. Its biological properties, which include biocompatibility, biodegradability, antimicrobial activity, biosafety, and non-toxicity, further enhance its utility. These biological attributes vary in their effects on plants and their associated pathogens, including fungal, bacterial, viral, viroid, and nematode pathogens (Wang *et al.*, 2005; Oliveira *et al.*, 2012) ^[53, 11]. Given these properties, chitosan is highly recommended for use in management strategies against a range of phytopathogens. Its efficacy in controlling viruses, bacteria, and fungi makes it a valuable tool in sustainable plant disease management practices (Divya *et al.*, 2017) ^[12].

Antimicrobial Properties of Chitosan against Phytopathogens

Several hypotheses have been proposed to explain the antimicrobial mechanisms of chitosan against various phytopathogens (Figure. 1).

Electrostatic Interactions

Chitosan's polycationic nature allows it to interact with the negatively charged components on the microbial cell surface. The positive amino glucosamine groups ($-NH_3^+$) in chitosan bind with the negative charges found in teichoic acids of gram-positive bacteria, lipopolysaccharides of

gram-negative bacteria, and phospholipids in fungal cell membranes. This interaction disrupts cell permeability, leading to leakage of intracellular electrolytes and proteins, ultimately resulting in cell death.

Chelation of Metals and Nutrients

Chitosan acts as a chelating agent for metals and essential nutrients, which can lead to microbial starvation and inhibit growth. The amine groups in chitosan facilitate the binding of metal cations, and this chelating ability is enhanced at high pH levels where the amine groups are deprotonated and available for interaction with metal ions (Guo *et al.*, 2006) ^[21].

Reduction of Membrane Permeability

High molecular weight chitosan can form a polymer coating on microbial cell surfaces, which may reduce cell membrane permeability and block access to essential nutrients. This coating effect impairs microbial development by restricting nutrient uptake.

Inhibition of Nucleic Acid Synthesis

For low molecular weight chitosan, internal electrostatic interactions occur between the positive amino groups on the polysaccharide chain and the negative phosphate groups on microbial nucleic acids. This interaction can inhibit the synthesis of DNA and mRNA, leading to a decrease in protein and enzyme production, further contributing to microbial inhibition.

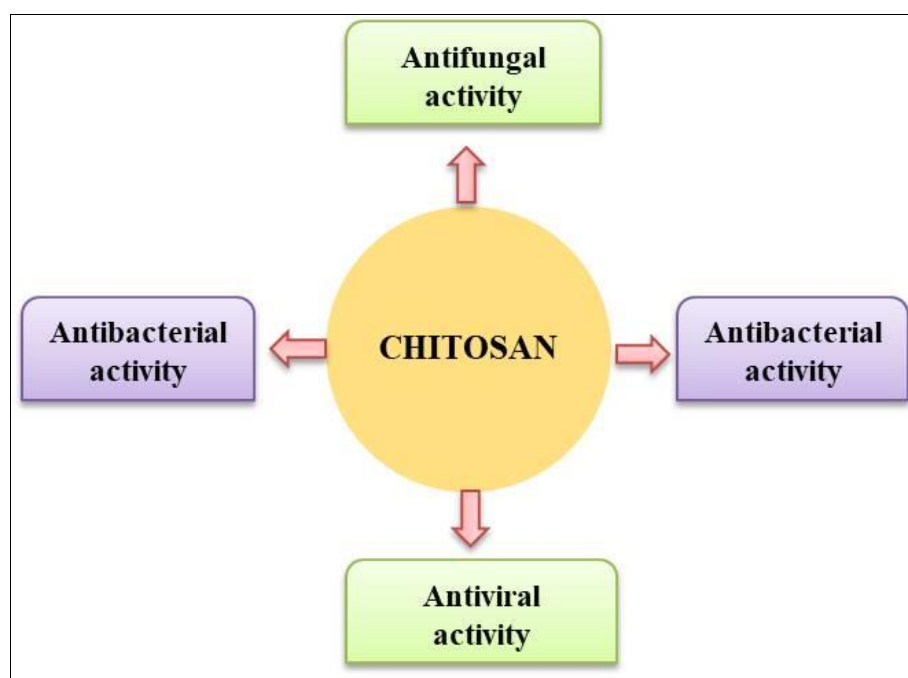


Fig 1: Antimicrobial properties of Chitosan

Antifungal Activity

Chitin exhibits potent antifungal properties, making it a crucial component in the fight against plant pathogenic fungi. The effectiveness of chitin in inhibiting fungal growth depends on factors such as its degree of polymerization, concentration, type of fungus, and environmental conditions (De Oliveira Jr *et al.*, 2012) ^[11]. When applied, chitin can interact with the fungal cell wall, composed mainly of

glucans and chitin itself, leading to the disruption of cell wall synthesis and structural integrity. This disruption results in the leakage of intracellular components, ultimately causing cell death (Guo *et al.*, 2006) ^[21].

Furthermore, chitin's antifungal activity is influenced by its ability to induce plant defense mechanisms. It acts as an elicitor, triggering the production of reactive oxygen species (ROS) and other defense-related enzymes in plants,

enhancing their resistance to fungal pathogens (Chakraborty *et al.*, 2020) ^[10]. For instance, the application of chitin on tomato plants has been shown to reduce the severity of Fusarium wilt by inducing systemic resistance. Similarly, chitin treatments in cucumber plants have significantly decreased the incidence of powdery mildew by boosting plant immunity (Gao & Shi, 2015) ^[18].

Recent studies have also highlighted chitin's potential in combination with other biocontrol agents. For example, a study demonstrated that combining chitin with *Trichoderma* spp. enhanced the suppression of *Rhizoctonia solani* in rice plants by improving the colonization efficiency of the biocontrol agent and inducing stronger plant defenses (El Hadrami *et al.*, 2010) ^[14]. Additionally, chitin's chelation properties allow it to bind to metal ions, which can inhibit fungal enzymes critical for their growth and pathogenicity (Gornik *et al.*, 2020) ^[19]. These combined effects make chitin a versatile and effective antifungal agent in sustainable agriculture practices.

Antibacterial Activity

Chitosan exhibits strong antibacterial properties against a range of plant pathogenic bacteria, including *Staphylococcus aureus*, *Streptomyces scabies* (Beausejour *et al.*, 2003) ^[7], *Ralstonia solanacearum*, *Xanthomonas* species, *Pseudomonas* species, and *Acidovorax* species. The effectiveness of chitosan in inhibiting bacterial growth varies depending on factors such as molecular weight, concentration, solvent type, bacterial classification (gram-positive or gram-negative), cell wall structure, incubation period, and other environmental conditions (Li *et al.*, 2010; Annaian *et al.*, 2016) ^[30, 5]. At low concentrations (below 0.2 mg/ml), chitosan binds to the negatively charged bacterial surface, leading to agglutination. However, at higher concentrations, the increased positive charge of chitosan can result in bacteria remaining suspended. Goy *et al.*, 2016 ^[20] proposed that chitosan may hydrolyze peptidoglycans, the primary component of bacterial cell walls, leading to electrolyte leakage and the death of the pathogens.

Additionally, Liang *et al.* 2014 ^[32] reported that chitosan causes bacterial cell membrane disruption, leading to cell death due to the leakage of intracellular contents. For instance, chitosan application on tomato plants inhibited the growth of *Xanthomonas vesicatoria*, while it protected cucumbers from *Pseudomonas syringae* pv. *lachrymans*, which causes bacterial angular leaf spot. Furthermore, chitosan reduced the incidence of disease in broccoli infected with *Pseudomonas fluorescens* and significantly decreased the disease index in watermelon seedlings infected with *Acidovorax citrulli* at a concentration of 0.4 mg/ml. A chitosan solution at 0.10 mg/ml notably reduced the number of surviving cells of *Xanthomonas* bacteria isolated from different geographical regions compared to the control after six hours of incubation, regardless of the bacterial strain (Divya *et al.*, 2017) ^[12].

Antiviral Activity

Chitosan's antiviral potential extends beyond just its effects on Potato Virus X (PVX) and Tobacco Mosaic Virus (TMV). It has been shown to activate various plant defense pathways, including the production of reactive oxygen

species (ROS) and the enhancement of enzyme activities like chitinases and glucanases, which play crucial roles in plant defense. Additionally, chitosan can form protective films on plant surfaces, acting as a physical barrier to virus entry. The polysaccharide's ability to trigger systemic resistance is not limited to specific crops, making it a versatile tool in managing viral infections across different plant species. Moreover, the synergistic effects of chitosan when combined with other antiviral agents or treatments can amplify its effectiveness, offering a more comprehensive strategy against plant viruses.

Viral diseases are among the most devastating plant diseases, causing significant harm to various plant species, thereby threatening agroecosystems and food security. Consequently, there is an urgent need for eco-friendly technologies to combat viral plant diseases and ensure the nutrients necessary to sustain the global population. Chitosan and its derivatives have emerged as promising tools in the fight against plant viruses. Chitosan has shown antiviral effects against Potato Virus X (PVX) in potato plants, possibly by inducing resistance and activating defense mechanisms or by inhibiting the systemic spread of the virus. Although the complete inhibition of virus multiplication in the host plant has not been fully confirmed, it is hypothesized that chitosan may interfere with viral replication by binding to the virus's nucleic acids, potentially damaging the viral genome (Dong *et al.*, 2019) ^[13]. Jia *et al.* 2016 ^[26] demonstrated chitosan's role in triggering systemic acquired resistance in *Arabidopsis* plants infected with Tobacco Mosaic Virus (TMV), identifying the signaling pathways involved in the plant's defense mechanisms. Their findings revealed that chitosan induced TMV resistance through the jasmonic acid pathway in *Arabidopsis* plants deficient in this pathway (*jar1*), but not in plants deficient in the salicylic acid pathway (*NahG*). Another study by Abdelkhale *et al.*, 2021 investigated the effects of chitosan as a protective and curative agent against Alfalfa Mosaic Virus (AMV) in *Nicotiana glutinosa* plants under greenhouse conditions. The results showed a significant reduction in AMV concentration, with a decrease of 70.43% in protective treatments and 61.65% in curative treatments. Additionally, the induction of systemic resistance and activation of defense mechanisms were observed, including increased levels of total phenols, carbohydrates, phenylalanine ammonia-lyase (PAL), and peroxidase (Ke *et al.*, 2021; Chakraborty *et al.*, 2020) ^[27, 10].

Antinematode activity

Nematode infestations cause severe damage and economic losses to a wide range of plant hosts, including fruit trees, vegetables, agronomic crops, foliage crops, grasses, nuts, and forest trees. Over 2,000 species of higher plants suffer economic losses, particularly in warm regions around the globe. There is an urgent need for new, eco-friendly nematode management strategies, such as biological control, natural products, plant extracts, and botanical products, to reduce the reliance on highly toxic chemical nematicides (Akhter *et al.*, 2018) ^[2]. Research by El-Ansary *et al.*, 2013 ^[15] showed that chitosan significantly decreased the severity of root-knot nematode infections caused by *Meloidogyne incognita* in banana plants (cv. Williams), leading to improved plant growth and yield.

Chitosan-treated tomato plants also exhibited reduced nematode reproduction, resulting in enhanced root and shoot size, weight, and overall plant growth. More recently, Khan *et al.*, 2021^[28] evaluated the efficacy of chitosan as a nematicide against infestations by *Megalaima incognita* in carrot plants under both *in vivo* and *in vitro* conditions. They found that different concentrations of chitosan (500, 1000, 1500, 2000, and 2500 ppm) affected egg masses and second-stage juveniles (J2s) of *M. incognita*. The highest concentration of 2500 ppm resulted in maximum mortality of J2s and the greatest inhibition of egg hatching after 36 hours of incubation.

Beyond its role in reducing nematode populations, chitosan has been found to enhance soil health by promoting the growth of beneficial microorganisms that can outcompete or antagonize nematodes. Its application not only disrupts the life cycle of nematodes by inhibiting egg hatching and juvenile development but also improves plant vigor, making plants more resilient to nematode attacks. Chitosan's biodegradable nature makes it an environmentally sustainable option for nematode management, reducing the reliance on harmful chemical nematicides. Recent studies also suggest that integrating chitosan with other biocontrol agents or organic amendments could further enhance its nematicidal efficacy while contributing to the overall health of the agroecosystem (Singh *et al.*, 2019)^[49].

Role of chitosan in plant protection against abiotic stress

Abiotic stresses such as drought, salinity, extreme temperatures, heavy metals, and oxidative stress are significant factors that adversely affect plant growth, productivity, and survival. These stress factors disturb plant physiological and biochemical processes, leading to reduced agricultural yield and food security concerns. In recent years, chitosan, a natural biopolymer derived from chitin, has gained attention due to its potential to enhance plant tolerance against various abiotic stresses. Its biocompatibility, biodegradability, and eco-friendliness make it an ideal agent for sustainable agriculture. Chitosan plays a crucial role in mitigating the effects of abiotic stress by regulating plant physiological processes, enhancing stress-responsive gene expression, and activating antioxidant defense systems.

Drought Stress

Drought is one of the most severe abiotic stressors that limit plant growth by impairing water availability, leading to dehydration, reduced photosynthesis, and metabolic disruptions. Chitosan has been found to enhance drought tolerance by improving water-use efficiency and regulating stomatal conductance, which helps to reduce water loss through transpiration. Studies have shown that chitosan-treated plants exhibit increased leaf water content and root biomass under drought conditions, indicating improved water retention capacity (Farouk *et al.*, 2012)^[16]. Additionally, chitosan can stimulate the accumulation of osmoprotectants such as proline and soluble sugars, which help maintain cell turgor and protect cellular structures from desiccation.

The application of chitosan also triggers the expression of drought-responsive genes, including those involved in abscisic acid (ABA) signaling pathways. ABA plays a key

role in regulating stomatal closure during drought, and chitosan treatment enhances ABA synthesis, leading to better drought adaptation (Aranaz *et al.*, 2013)^[6]. Moreover, chitosan enhances the antioxidant defense system by upregulating antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which reduce oxidative damage caused by reactive oxygen species (ROS) during drought stress.

Salinity Stress

High salinity, often due to excessive salt accumulation in the soil, is another major abiotic stress that hampers plant growth by causing ion toxicity, osmotic stress, and nutrient imbalances. Chitosan has been shown to alleviate salinity stress by enhancing ion homeostasis, particularly by reducing sodium (Na⁺) uptake and increasing potassium (K⁺) content in plants. This selective ion uptake helps maintain cellular osmotic balance, allowing plants to cope with the high osmotic pressure induced by salt stress.

Chitosan also promotes the synthesis of stress-related proteins and osmolytes such as glycine betaine, which help stabilize membranes and protect plants from the damaging effects of salinity (Gao *et al.*, 2015)^[18]. Furthermore, chitosan application induces the expression of salinity-responsive genes, including those involved in ion transport and stress signaling pathways. Studies on crops like rice and tomato have demonstrated that chitosan treatment improves seed germination, root growth, and overall plant biomass under saline conditions (Jabeen *et al.*, 2019)^[25]. Another significant benefit of chitosan in mitigating salt stress is its ability to enhance the antioxidant defense system. Under salinity stress, the production of ROS increases, leading to oxidative damage to cellular components such as lipids, proteins, and DNA. Chitosan-treated plants exhibit higher levels of antioxidant enzymes, which scavenge ROS and protect cells from oxidative damage, thereby improving plant tolerance to salinity stress.

Temperature Stress (Heat and Cold)

Extreme temperatures, including both heat and cold stress, can severely affect plant growth, development, and productivity. Heat stress leads to protein denaturation, membrane destabilization, and disrupted photosynthesis, while cold stress affects membrane fluidity, enzyme activity, and nutrient uptake. Chitosan has been found to mitigate both heat and cold stress by enhancing the expression of heat shock proteins (HSPs) and cold-responsive proteins (CRPs), which protect cellular structures from temperature-induced damage. In the case of heat stress, chitosan application has been shown to improve photosynthetic efficiency by stabilizing chloroplast membranes and protecting the photosystem from heat-induced damage. Additionally, chitosan-treated plants exhibit increased levels of antioxidants such as glutathione and ascorbate, which play a critical role in mitigating oxidative stress caused by high temperatures. For cold stress, chitosan enhances the accumulation of osmoprotectants like proline and trehalose, which help maintain membrane integrity and protect plants from freezing damage. Furthermore, chitosan induces the expression of cold-responsive genes involved in the regulation of membrane fluidity and ROS detoxification,

contributing to improved cold tolerance (Khan *et al.*, 2018) [29].

Heavy Metal Stress

Heavy metal contamination in soils, caused by industrial activities and the excessive use of fertilizers and pesticides, poses a serious threat to plant health. Metals such as cadmium (Cd), lead (Pb), and mercury (Hg) can accumulate in plants, causing toxicity and disrupting physiological processes like photosynthesis, respiration, and nutrient uptake. Chitosan has demonstrated a protective role in mitigating heavy metal stress by chelating metal ions and reducing their bioavailability to plants (Gornik *et al.*, 2020) [19]. Chitosan forms complexes with heavy metal ions, preventing their uptake and translocation to plant tissues. This reduces the toxic effects of metals on plants and improves their growth and development.

Moreover, chitosan enhances the expression of metal detoxification-related genes and proteins, including metallothioneins and phytochelatins, which play essential roles in sequestering and detoxifying heavy metals. Additionally, chitosan boosts the activity of antioxidant enzymes, reducing oxidative damage caused by heavy metal-induced ROS. Studies on plants like maize and soybean have shown that chitosan application significantly reduces the accumulation of heavy metals in plant tissues while improving plant growth and physiological functions.

Oxidative Stress: Oxidative stress is a common consequence of various abiotic stress factors, such as drought, salinity, and heavy metals, leading to excessive ROS accumulation. ROS, including superoxide radicals and hydrogen peroxide, can damage cellular components, resulting in cell death and reduced plant growth. Chitosan plays a vital role in alleviating oxidative stress by enhancing the antioxidant defense system in plants. Chitosan-treated plants exhibit increased activity of antioxidant enzymes such as SOD, CAT, and POD, which detoxify ROS and protect cells from oxidative damage. Additionally, chitosan induces the synthesis of non-enzymatic antioxidants such as flavonoids, ascorbate, and glutathione, which further enhance the plant's ability to scavenge ROS and maintain cellular homeostasis under stress conditions. Through these mechanisms, chitosan improves plant resilience to oxidative stress, promoting better growth and productivity under adverse environmental conditions.

The role of chitosan in enhancing plant characteristics

Chitosan, a natural biopolymer derived from chitin, has gained significant attention in agriculture due to its potential to enhance various plant traits. This polysaccharide is obtained primarily from the exoskeletons of crustaceans, insects, and fungal cell walls, and it is widely recognized for its biocompatibility, biodegradability, and non-toxicity. Chitosan's application in agriculture is multifaceted, encompassing roles in plant growth promotion, stress tolerance, disease resistance, and the improvement of crop yield and quality. Below is a detailed exploration of chitosan's role in enhancing plant traits:

Plant Growth Promotion

Chitosan has been shown to promote plant growth by

influencing several physiological processes. It can stimulate seed germination, root development, and overall plant biomass. The application of chitosan can lead to increased nutrient uptake, particularly nitrogen, phosphorus, and potassium, which are essential for plant growth. Mechanism of action includes Chitosan can modulate plant hormone levels, particularly auxins and gibberellins, which play a crucial role in root elongation and cell division. Additionally, it enhances the activity of key enzymes involved in nutrient assimilation and metabolism (El Hadrami, *et al.*, 2010; Al-Turki, *et al.*, 2021) [14, 4].

Enhanced Disease Resistance

Chitosan acts as an elicitor of plant defense responses, triggering the production of various defense-related compounds such as phytoalexins, pathogenesis-related (PR) proteins, and reactive oxygen species (ROS). These compounds enhance the plant's ability to resist infections by various pathogens, including fungi, bacteria, and viruses. Mechanism includes Chitosan can activate the plant's innate immune system by binding to specific receptors on the plant cell surface, leading to the activation of signaling pathways that induce systemic acquired resistance (SAR) and localized defense responses (Iriti & Varoni, 2015; Campos *et al.*, 2021) [24, 9].

Abiotic Stress Tolerance

Chitosan has been found to enhance plant tolerance to various abiotic stresses, such as drought, salinity, and heavy metal toxicity. By improving water use efficiency, osmotic balance, and antioxidant capacity, chitosan-treated plants can better withstand adverse environmental conditions. Mechanism includes Chitosan enhances the synthesis of osmoprotectants like proline and soluble sugars, which help maintain cellular osmotic balance under stress. It also boosts the activity of antioxidant enzymes, reducing oxidative damage caused by stress-induced ROS (Farouk, *et al.*, 2020) [17].

Improved crop yield and quality

Chitosan application has been associated with improved crop yield and quality. It enhances fruit set, size, and nutritional content in various crops, including tomatoes, strawberries, and cereals. Chitosan also improves the post-harvest shelf life of fruits and vegetables by reducing decay and maintaining freshness. Mechanism includes the biostimulatory effect of chitosan on fruit development is linked to its ability to enhance nutrient translocation, increase photosynthetic activity, and improve water retention in plant tissues. Additionally, its antimicrobial properties help reduce post-harvest losses.

Induced Systemic Resistance (ISR)

Chitosan can induce systemic resistance in plants, leading to long-lasting protection against a broad spectrum of pathogens. Unlike SAR, which involves the salicylic acid pathway, ISR primarily depends on the jasmonic acid and ethylene signaling pathways. Mechanism includes chitosan triggers the ISR pathway by activating gene expression related to defense mechanisms without directly involving the pathogen. This priming effect ensures that plants can respond more rapidly and robustly to subsequent attacks (Li,

et al., 2020) [31].

Chitosan in Sustainable Agriculture

In the context of sustainable agriculture, chitosan represents an eco-friendly alternative to synthetic chemicals for enhancing plant traits. Its biodegradability and non-toxic nature make it a valuable tool for reducing the environmental impact of agricultural practices while maintaining or improving crop productivity. Chitosan's role in enhancing plant traits is well-established, offering benefits ranging from growth promotion and improved yield to increased stress tolerance and disease resistance. Its versatility and sustainability make it a valuable tool in modern agriculture, contributing to both productivity and environmental conservation. Continued research and development in this area are likely to expand the applications of chitosan in crop management, paving the way for more resilient and productive agricultural systems.

Future Aspects

Future research on chitosan in sustainable plant disease management should focus on optimizing formulations for various crops and environmental conditions, ensuring consistent efficacy. The development of chitosan-based nanomaterials could enhance its antimicrobial properties and delivery mechanisms. Integrating chitosan with other biocontrol agents may offer synergistic effects, improving overall plant health. Additionally, exploring its role in enhancing plant resistance to abiotic stresses, such as drought and salinity, can expand its applications. Regulatory support and market acceptance are crucial for widespread adoption, making interdisciplinary collaboration essential for advancing chitosan's potential in sustainable agriculture.

Conclusion

Chitosan is an effective biopolymer for enhancing plant protection against various abiotic stresses, including drought, salinity, extreme temperatures, heavy metal toxicity, and oxidative stress. Its ability to regulate physiological processes, activate stress-responsive genes, enhance antioxidant defense systems, and improve ion homeostasis makes it a promising tool for sustainable agriculture. As research continues to explore the multifaceted roles of chitosan, its application as a plant protection agent could become an integral part of eco-friendly strategies to mitigate the impact of abiotic stress on crop productivity.

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Data Availability

There is not hidden data, all data are presented in this manuscript.

Ethical Statement

This study did not involve human or animal subjects; therefore, informed consent is not applicable.

Conflict of Interest: The authors declare that they have no

knows competing financial interests or personal relationship that could have approved to influence the work reported in this paper.

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