J. Sci. Innov. Nat. Earth: Vol. 5, Issue 2, 2025, Page 22-26 ISSN (Online) 2583-2093 OPEN ACCESS

Journal of Science Innovations and Nature of Earth

Journal homepage : https://jsiane.com/index.php/files/index

International, Double-Blind, Quarterly, Peer-Reviewed, Refereed Journal, Edited and Open Access Research Journal

Role of Chitosan as a Natural Elicitor in Inducing Systemic Resistance against Plant Pathogens

Sangeeta Yadav[1] and Devesh Kumar[1]*

[1]Department of Botany, RBS College, Agra, Affiliated to Dr. Bhimrao Ambedkar University, Agra, Uttar Pradesh, India

*Corresponding Author E-mail: drdeveshjadon@gmail.com

DOI: https://doi.org/10.59436/jsiane.375.2583-2093

Abstract

Chitosan is a biopolymer of natural origin produced by modification of chitin. Chitin is abundantly found in cell walls of fungi, shells of crustaceans and insect exoskeleton. Chitin to chitosan transformation involves removal of acetyl groups from the chitin structure. The deacetylation process converts chitin into chitosan. Chitosan is a biodegradable and nontoxic biopolymer. In agriculture, chitosan has gained popularity as a natural elicitor that stimulates the plant's own defence system without directly killing pathogens. Instead of acting as a pesticide, chitosan acts as immunity booster in plants, allowing them to defend themselves against a variety of diseases. This review focusses on chitosan's role in inducing systemic defence mechanisms in plants, as well as the underlying physiological and molecular responses triggered by chitosan application.

Keywords*:* Chitosan, Chitin, sustainable crop protection, chitosan nanoparticles

Received 20.03.2025 Revised 15.04.2025 Accepted 10.05.2025 Online Available 03.06.2025

Introduction

As awareness grows about the harmful effects of chemical pesticides on the environment, human health, and food safety, it has become increasingly important to adopt sustainable and environmentally friendly approaches to protect crops in today's agricultural practices. Overusing synthetic agrochemicals like fungicides and insecticides has caused several serious problems. It has led to pollution of the environment, the development of pest and disease-causing organisms that are no longer affected by these chemicals, and a noticeable reduction in the variety of beneficial organisms living in the soil (Popp *et al*., 2013). In this regard, researchers and agricultural practitioners are increasingly looking into biological and natural alternatives that are both effective and environmentally friendly.

Chitosan has emerged as a potentially effective natural pesticide alternative. It is a biopolymer derived from chitin, which is abundant in crustacean outer shells such as crabs and prawns, as well as fungal cell walls and insect exoskeleton (Rinaudo, 2006). Chitosan's eco-friendliness makes it especially useful in sustainable farming—it is biodegradable, non-toxic, and safe for both plants and the environment. Unlike conventional pesticides, which kill harmful organisms directly, chitosan strengthens the plant's natural defence system. It acts as a natural trigger, allowing plants to recognise and respond more effectively to potential pathogen threats (Maleki *et al*., 2020; El Hadrami *et al*., 2010). The research into the use of chitosan as a plant defence elicitor began with the pioneering work of Allan and Hadwiger in 1979, who were among the first to show that chitosan, a naturally occurring biopolymer derived from chitin, could induce resistance responses in plants. Their research found that applying chitosan to pea pods activated pathogenesis-related (PR) proteins, implying that it can boost plant immunity without directly targeting the pathogen (Allan & Hadwiger, 1979). This breakthrough was a watershed moment in plant immunology research, introducing the concept of using a natural, biodegradable compound to elicit defence responses in host plants. Since its discovery, chitosan has been the focus of extensive research over the past forty years, revealing its diverse and valuable roles in plant protection. Studies have shown that chitosan not only helps defend plants against diseases caused by pathogens but also boosts their resilience to environmental stresses. Acting as a priming agent, it prepares plants to better handle challenges like high salinity, drought, heavy metal exposure, and extreme temperatures. It does this by enhancing the activity of antioxidant enzymes, promoting the buildup of protective compounds like proline and soluble sugars, and helping maintain the stability of cell membranes during stress (Kashyap *et al*., 2020).

Chitosan plays a key role in boosting a plant's natural defence system. It activates specific defence-related genes and encourages the production of protective compounds like phenolics and phytoalexins. Additionally, it helps strengthen the plant's physical barriers by promoting the buildup of substances like callose and lignin at the sites of infection (Hidangmayum *et al*., 2019). This process, known as immune priming, allows the plant to react faster and more effectively when attacked by pathogens. Importantly, it does so without constantly using up energy, unlike continuous defence mechanisms, making the plant's response both efficient and energy-saving.

In addition, chitosan triggers several important signalling pathways in plants specifically those involving jasmonic acid (JA), salicylic acid (SA), and ethylene signalling. These pathways are crucial for activating the plant's long-term defence mechanisms, known as systemic acquired resistance (SAR) and induced systemic resistance (ISR). By stimulating these pathways, chitosan helps the plant build a stronger and more coordinated immune response throughout its entire system. This demonstrates its unique ability to mediate biotic and abiotic stress responses, thereby contributing to overall plant resilience (El Hadrami *et al*., 2010). In an era of climate change and ecological degradation, where reliance on synthetic agrochemicals is becoming unsustainable, chitosan emerges as a promising, environmentally friendly solution. Its natural origin, environmental safety, and broad-spectrum efficacy have propelled it to the forefront of research on sustainable plant disease and stress management. When chitosan is applied externally to plants, it sets off a series of defence responses. These include the generation of reactive oxygen species (ROS), strengthening of the cell wall, production of antimicrobial compounds like phytoalexins, and activation of various defence-related genes. ROS, in particular, create oxidative stress that can damage proteins and genetic material, eventually leading to the death of infected cells. These reactions help enhance the plant's overall resistance, making it more capable of withstanding infections caused by fungi, bacteria, and viruses (Xing *et al*., 2015). Since chitosan boosts the plant's own immune system rather than directly attacking the pathogens, it also lowers the chances of pests or pathogens developing resistance over time.

Plants are regularly subjected to a large number of abiotic and biotic stressors, including salinity, which disrupts cellular homeostasis and leads to overproduction of Reactive Oxygen Species (ROS), such as superoxide anions (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals (•OH). Although ROS act as signalling molecules at low concentrations, excessive accumulation during salinity stress causes oxidative damage to lipids, proteins, nucleic acids, and membranes (Gill & Tuteja, 2010). To combat ROS, plants use a two-tiered antioxidant defence system that includes both enzymatic and non-enzymatic components. Plants use a variety of non-enzymatic antioxidants that include phenolic compounds, flavonoids, carotenoids, vitamin C (ascorbic acid), glutathione, and vitamin E (α-tocopherols), as well as enzymes like CAT (Catalase) and SOD (Superoxide dismutase). These molecules directly neutralise ROS, thus, upholding redox balance and protecting cells from oxidative injury (Gerami *et al*., 2020; Sen *et al*., 2020; Sheikhalipour *et al*., 2021).

In the face of increasing variability in the environment, chitosan has emerged as a potent biostimulant and natural elicitor capable of improving plant defence against both biotic (pathogen-related) and abiotic (environmental) stresses. Chitosan application has been shown to activate plant defence pathways, increase the level of phenolic metabolites and flavonoids, and improve the synthesis of protective molecules such as proline and phytoalexins (Saberi-Riseh *et al*., 2021). This multifaceted response assists plants in maintaining physiological and metabolic balance under adverse conditions such as salinity, drought, or pathogen attack.

The versatility of chitosan makes it a promising alternative to synthetic agrochemicals, especially in the context of climate change and global food security. Excessive use of chemical fertilisers and pesticides to address rising stressors has resulted in soil degradation, pollution, and ecosystem imbalance. Chitosan, on the other hand, naturally promotes stress adaptation by inducing systemic resistance, increasing antioxidative capacity, and improving crop resilience without harming the environment (Maleki *et al*., 2020).

Structure and Physico-chemical Properties of Chitosan

Chitosan is a naturally derived linear polysaccharide, obtained by partially or fully removing acetyl groups from chitin (see Figure 1). It ranks as the second most abundant natural polymer after cellulose. The structure of chitosan is made up of repeating units of two sugar components: D-glucosamine (where acetyl groups have been removed) and N-acetyl-D-glucosamine (which still contains the acetyl groups). These units are connected by β-(1→4) linkages, giving chitosan a molecular framework similar to that of cellulose (Rinaudo, 2006).

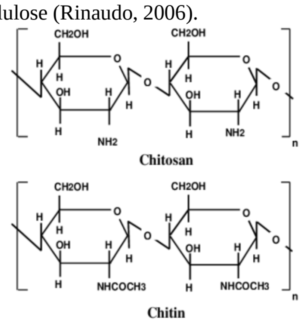

Figure-1: Chemical structure of chitosan and chitin

The physico-chemical properties of chitosan, specifically its degree of deacetylation (DD), molecular weight (MW), and the solubility, have a significant impact on its biological activity and effectiveness in agricultural and biomedical applications. Deacetylation increases the count of free amino groups ($-NH_2$), making it more soluble in acidic solutions and capable of forming complexes with other molecules. Similarly, lower molecular weight chitosan is more water-soluble and easily absorbed by biological membranes, making it a better elicitor or antimicrobial agent (Pillai *et al*., 2009; Maleki *et al*., 2020). One of the unique features that sets chitosan apart from most other natural polysaccharides is its positive charge. This cationic nature allows chitosan to interact easily with negatively charged substances, such as phospholipids found in the membranes of microbes, certain proteins, and pectins in plant cell walls. These electrostatic interactions typically occur in mildly acidic environments (with a pH below 6.5), enhancing chitosan's ability to bind and exert its biological effects (Younes & Rinaudo, 2015). This property not only improves chitosan's antimicrobial activity by disrupting microbial cell membranes, but it also makes it useful as a plant defence elicitor, as it can bind to receptor molecules on plant surfaces and initiate defence signalling cascades. When chitosan comes into contact with plant cells, it often triggers several early defence responses. These include changes in the electrical charge across the plasma membrane (known as membrane depolarisation), an increase in calcium ion levels inside the cell, and the generation of reactive oxygen species (ROS). These reactions play a crucial role in initiating the plant's immune system and preparing it to defend against potential threats (El Hadrami *et al*., 2010). Furthermore, the polymer's ability to form gels, films, and nanoparticles expands its application in agricultural formulations, allowing for controlled release of nutrients or elicitors and improved adhesion to plant surfaces. Thus, chitosan's structural flexibility and multifunctional properties make it a versatile biopolymer for improving plant growth and disease resistance, thereby contributing significantly to sustainable agriculture.

Plant Defence Responses Elicited by Chitosan Chitosan, a natural compound obtained from chitin, acts as an effective elicitor by activating a wide array of plant defence mechanisms both at the site of infection and throughout the entire plant system. These defence responses involve hormone signalling pathways, strengthening of cell structures, rapid production of reactive oxygen species (oxidative bursts), activation of defence-related genes, and synthesis of protective secondary metabolites. Together, these processes enhance the plant's ability to resist attacks from a broad spectrum of pathogens. The table below provides the major defensive mechanisms activated by chitosan in various plant systems, along with key literature supporting each finding:

Table 1: Plant Defense Responses Elicited by Chitosan

Plant Defence Response	Explanation	References
Abscisic acid (ABA)	Chitosan induces ABA synthesis. ABA is a stress hormone involved in stomatal closure and pathogen response modulation.	Iriti & Faoro, 2008
Calcium transient	Chitosan induces rapid Ca^{2+} influx. Ca^{2+} acts as secondary messenger and its signalling event triggering downstream defence responses.	Kauss, 1985; Zuppini *et al.*, 2003
Callose deposition	Chitosan stimulates plants to deposit callose at the areas where infection occurs. This forms a physical barrier that helps block the entry and spread of pathogens within plant tissues.	Faoro *et al.*, 2008
Lignin biosynthesis	Chitin and chitosan promote lignin accumulation, which strengthens cell walls and creates a physical barrier to pathogens.	Pearce & Ride, 1982; Kohle *et al.*, 1985
Hypersensitive response (HR)	Chitosan triggers a hypersensitive response (HR) in plants, which leads to the deliberate death of cells at the site of infection. This localized cell death acts as a defence strategy to limit the spread of the invading pathogen to surrounding healthy tissues	Zuppini *et al.*, 2003, Iriti *et al.*, 2006, Wang *et al.*, 2008
Tyloses formation	Induces development of tyloses in xylem vessels to block the movement pathogen through xylem.	Lafontaine & Benhamou, 1996
Jasmonic acid (JA) signalling	Rising JA accumulation, activating ISR and providing defence against necrotrophic pathogens.	Doares *et al.*, 1995
MAP kinase activation	Chitosan stimulates mitogen-activated protein kinases (MAPKs) involved in signal transduction for defence related gene expression.	Hu *et al.*, 2004; Lizama-Uc *et al.*, 2007
Metabolite production	Chitosan boosts the production of important protective compounds in plants, including ascorbate, glutathione, flavonoids, and polyamines. These metabolites play key roles in strengthening the plant's defence system by helping to neutralize harmful molecules.	Li *et al.*, 2017
Pathogenesis-Related (PR) proteins	Chitosan stimulates the expression of pathogenesis-related (PR) genes, particularly those responsible for producing enzymes like chitinases and β-1,3-glucanases. These enzymes break down components of fungal cell walls, thereby helping the plant to defend itself more effectively against fungal infections.	Walker-Simmons *et al.*, 1984, Agrawal *et al.*, 2002, Romanazzi *et al.*, 2002, Lizama-Uc *et al.*, 2007
Phytoalexin production	Chitosan stimulates the production of phytoalexins, such as pisatin and resveratrol, which inhibit pathogen growth.	Agrawal *et al.*, 2002, Chakraborty *et al.*, 2008, Khan *et al.*, 2003
Plasma membrane H^+-ATPase inhibition	Chitosan modulates the electrical activity of the plant cell membrane and regulates ion movement, making it difficult for pathogens to establish and spread.	Amborabe *et al.*, 2008
Phenolic compound accumulation	Improves the synthesis of phenolic acids and flavonoids, which have antimicrobial and antioxidant properties.	El-Hassni *et al.*, 2004
Reactive oxygen species (ROS) burst	Chitosan increases the production of reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2). These molecules act as both signals to trigger defence responses and as antimicrobial agents that help the plant fight off invading pathogens.	Lin *et al.*, 2005, Wang *et al.*, 2008
Systemic Acquired Resistance (SAR)	Chitosan activates pathways linked to SAR, which is a defence mechanism that provides long-lasting and wide-ranging protection against various pathogens. This response helps the entire plant build immunity, not just at the infection site,	Iriti *et al.*, 2006

	but throughout its tissues.	
Terpenes	Chitosan promotes the production of terpenoids that play an important role in plant defence. These molecules aid plants in responding to stress and pathogen attacks. They act as both direct antimicrobial agents and signals that activate other protective responses.	Croteau *et al.*, 1987

Mechanism of Action as an Elicitor

Recognition by Plant Receptors- Chitosan initiates plant defence responses by first being recognized at the surface of plant cells. Plants possess sophisticated immune systems that can detect potential threats through special receptors located in their plasma membranes, known as pattern recognition receptors (PRRs). These receptors identify common molecular structures found in microbes, called pathogen-associated molecular patterns (PAMPs) or microbe-associated molecular patterns (MAMPs), allowing the plant to sense the presence of an invader and activate its defence mechanisms. Chitosan, which is structurally similar to fungal cell wall components, is recognised as a non-self molecular signal, similar to a PAMP (De Oliveira *et al*., 2016). When chitosan comes into contact with the plant cell wall, it binds to specific receptors on the cell's surface, such as receptor-like kinases or proteins. This binding activates the plant's initial immune response, known as pattern-triggered immunity, which is its first line of defence against potential pathogens. (Boller & Felix, 2009).

This recognition event occurs quickly and initiates a complex network of signalling cascades aimed at improving the plant's defence. Chitosan recognition triggers early defence responses, which include:

•Ion fluxes, particularly calcium influx through the plasma membrane. Calcium act as a secondary messenger.

•Depolarisation of the membrane potential alters the cellular ion balance.

•A rapid increase in reactive oxygen species (ROS), like hydrogen peroxide (H_2O_2), occurs as an early defence response. These molecules not only help kill invading pathogens but also serve as important signals to trigger further immune reactions within the plant (Petrov *et al*., 2015).

•Alongside this, chitosan activates a series of mitogen-activated protein kinase (MAPK) cascades. These signalling pathways transmit the defence message from the cell surface to the nucleus, leading to changes in gene expression that prepare the plant for stronger defence (Yang *et al*., 2017).

These defence responses lead to the strengthening of the plant's physical barriers, such as the deposition of callose in the cell wall, and the closing of stomata to block pathogen entry. Additionally, genes linked to plant immunity become more active, equipping the plant to better resist infection. Notably, chitosan-triggered pattern-triggered immunity (PTI) doesn't kill pathogens outright. Instead, it prepares or "primes" the plant's immune system, enabling it to react more quickly and effectively when faced with future threats. (Maleki *et al*., 2020). Thus, recognition of plant PRR by chitosan mimics typical PAMP-triggered immune responses, establishing chitosan as a valuable natural elicitor for improving disease resistance in crops without the environmental risks associated with synthetic agrochemicals.

Induction of Systemic Resistance

Chitosan is well known for its capacity to activate defence responses across the entire plant, not just where it is applied. It helps trigger systemic immunity, preparing the whole plant to better defend itself against potential threats. This phenomenon is known as systemic resistance, and it can be classified into two types: SAR and ISR. Both types activate defence signalling networks and express protective compounds, but they differ in their signalling molecules and triggers.

SAR (Systemic Acquired Resistance)

SAR is a powerful and long-lasting defence strategy that protects plants against a wide range of pathogens. It is typically triggered by a localized infection or the presence of certain signalling compounds. Chitosan can mimic the effects of a pathogen attack, activating SAR by promoting the build-up of salicylic acid (SA), which is an important signalling molecule in this process. SA then initiates a chain of molecular responses, including the activation of specific defence genes like PR-1; PR-2; and PR-5. These genes produce proteins with antifungal and antimicrobial properties that help strengthen the plant's resistance throughout its entire system (Vlot *et al*., 2009). These proteins help to protect the plant's distal, uninfected parts by putting it on high alert, allowing it to respond faster to future attacks.

ISR (Induced Systemic Resistance)

Unlike SAR, which is mainly triggered by pathogen attacks, ISR is usually activated by beneficial soil microbes or non-living stimulants like chitosan. This form of resistance relies on signalling pathways involving jasmonic acid and ethylene (Pieterse *et al*., 2014). Chitosan enhances ISR by boosting the production of JA and ET, which in turn regulate various plant defence responses. These include reinforcing the cell wall, depositing lignin to create physical barriers, and producing protective secondary compounds like phytoalexins to fend off potential threats. Unlike SAR, ISR does not usually involve PR gene expression, but rather prepares the plant for faster activation of defences in response to pathogen attack.

Integration of SAR and ISR Responses

Remarkably, chitosan has the unique ability to trigger both SAR and ISR pathways simultaneously, providing plants with a robust and layered defence system. By activating these two immune responses at once, chitosan leads to the build-up of a wide range of protective compounds—including flavonoids, phenolics, and terpenoids—along with antimicrobial proteins and defence enzymes. Together, these elements form a coordinated shield that helps prevent pathogens from growing and spreading within the plant. (Rabea *et al*., 2003; Maleki *et al*., 2020). Furthermore, the oxidative burst caused by chitosan aids in signalling reinforcement and pathogen containment.

Chitosan-Mediated Defence Responses

Chitosan initiates a wide array of defence responses in plants upon application, functioning as a potential natural elicitor. These responses range from rapid cellular reactions to transcriptional and enzymatic changes, which together improve plant resilience to various biotic stresses.

Oxidative Burst and Cell Wall Reinforcement.

Plants respond quickly to chitosan by producing reactive oxygen species (ROS) like H_2O_2, O_2^-, and •OH. ROS have two functions: they act as antimicrobial agents, directly inhibiting pathogen growth, and as signalling molecules, activating downstream defence genes (Petrov *et al*., 2015).

Chitosan also causes the cell wall to be strengthened, which is an important physical barrier against pathogen invasion. This includes callose deposition, structural protein crosslinking, and lignin biosynthesis, all of which contribute to plant tissue mechanical strength. Lignin polymerisation, in particular, slows the spread of invading fungi and bacteria (Iriti & Faoro, 2009). These responses not only prevent the pathogen from spreading, but they also alert surrounding tissues to potential attacks.

Defence Gene Expression

Chitosan is essential for activating a wide range of defence-related genes in plants, many of which are associated with well-established immune signalling networks. Among the most important is the PR1 gene, which represents the salicylic acid-driven systemic acquired resistance (SAR) pathway. In addition to PR1, chitosan increases the activity of PAL (phenylalanine ammonia-lyase), a key enzyme in the phenylpropanoid pathway. This results in the production of a variety of protective compounds, including phytoalexins, flavonoids, and lignin precursors, all of which help the plant strengthen its structure and defend against invading pathogens. (Xing *et al*., 2015). Furthermore, the CHI (chitinase) genes, which encode enzymes that degrade fungal cell wall chitin, are activated. This implies that chitosan application not only primes the plant immune system, but also actively boosts antifungal potential through enhancement of structural and biochemical defences.

Enhanced Activity of Defence Enzymes

Elevated enzymatic defence activity is an important component of chitosan-induced resistance. Plants with treatment exhibit increased activity of chitinases, which break down fungal cell walls.

• Peroxidases catalyse lignin formation and ROS generation.

• β-1,3-glucanases break down fungal β-glucans.

•Polyphenol oxidases (PPOs) play a role in phenolic oxidation and pathogen-toxic browning reactions (Hadwiger, 2013).

Upregulation of these enzymes helps to degrade pathogen cell walls, localise infections, and strengthen structural barriers. Together, chitosan-induced enzymatic and molecular changes significantly reduce disease severity and improve plant tolerance to different pathogens.

Applications in Crop Protection

The use of chitosan as a natural biostimulant and elicitor has gained substantial attention now-a-days due to its demonstrated efficacy in inducing disease resistance across a wide range of crops. Its capability to elicit plant immune responses while not harming the environment makes it an appealing alternative to synthetic fungicides. Chitosan has been successfully used in a variety of agricultural systems, resulting in substantial decreases in disease incidence and fungicide dependency. The examples below indicate its potential in specific crop-pathogen interactions:

Tomato (*Solanum lycopersicum*)

Chitosan application to tomato plants has been found to significantly boost their resistance against harmful fungal diseases like Botrytis cinerea (which causes grey mould) and Alternaria solani (responsible for early blight). These fungi are notorious for damaging solanaceous crops, often leading to reduced yields and spoilage after harvest. Research by Ben-Shalom *et al*. (2003) revealed that chitosan treatment raised the levels of key defence proteins, including chitinases and β-1,3-glucanases—enzymes that break down fungal cell walls. This immune response helped reduce the size and spread of lesions caused by the fungi, highlighting chitosan's potential as an effective tool in managing tomato diseases as part of an integrated crop protection strategy.

Rice (*Oryza sativa*)

Rice blast is one of the most serious diseases in rice caused by the fungal pathogen Magnaporthe oryzae. It is one of the most damaging diseases in rice, affecting millions of hectares globally and leading to significant yield losses. Studies have shown that spraying rice plants with chitosan can help trigger systemic resistance, making the plant more capable of fighting off the infection. This is achieved by boosting the activity of key defence enzymes like peroxidase and phenylalanine ammonia-lyase (PAL), which play important roles in producing lignin and phenolic compounds—both of which strengthen plant cell walls and act as physical barriers to stop pathogen entry. Research by Yin *et al.* (2021) also found that chitosan not only lowered the severity of the disease but also activated early defence reactions, such as the buildup of hydrogen peroxide (H_2O_2) and the formation of callose, both of which are essential for stopping the fungus at the infection site.

Grapevine (*Vitis vinifera*)

Grapevines are extremely susceptible to downy mildew (Plasmopara viticola) and grey mould (Botrytis cinerea), both of which require frequent fungicide applications to control. However, overreliance on chemicals in viticulture raises concerns about environmental safety and the spread of pathogen resistance. Romanazzi *et al.* (2009) found that preharvest chitosan sprays significantly reduced disease incidence in grapes, improving both field resistance and postharvest fruit quality. Chitosan-treated plants showed increased activity of defence enzymes like chitinase and polyphenol oxidase, reducing the need for conventional fungicides. This supports the use of chitosan as a long-term, residue-free crop protection strategy in vineyards.

These examples demonstrate chitosan's broad-spectrum efficacy in managing plant diseases across a variety of crops. Chitosan reduces the risk of resistance development by priming host defence responses rather than directly acting on pathogens, thereby contributing to environmentally sustainable agriculture.

Synergy with Biological Control Agents and Nanotechnology

Increased demand for environmentally friendly and sustainable crop protection strategies has prompted research into the integration of chitosan, biological control agents (BCAs), and nanotechnology-based innovations. Chitosan's natural eliciting properties, when combined with beneficial microbes or delivered as nanoparticles, substantially improve the efficacy and dependability of plant defence mechanisms.

Synergy with Biological Control Agents

Chitosan has shown remarkable synergistic effects when applied alongside biological control agents like as Bacillus subtilis and Trichoderma spp. These microorganisms are well known for their ability to suppress pathogens via antibiosis, competition, and mycoparasitism, and also for activating ISR in host plants. When combined with chitosan, their effects are amplified, leading to stronger and more consistent activation of plant immunity (Gornik *et al*., 2008). The mechanism underpinning this synergy involves the dual stimulation of defence pathways: while chitosan acts as a PAMP mimic, activating salicylic acid mediated responses, BCAs primarily induce jasmonic acid and ethylene signalling, which is associated with ISR. This simultaneous activation of multiple pathways boosts broad-spectrum resistance and causes an increase in the accumulation of defence-related enzymes like peroxidases, PPO, and PAL. Additionally, these combinations promote root colonisation, nutrient uptake, and plant growth, resulting in a plant-protective microbiome that is more resistant to environmental stress and pathogen attack.

Integration with Nanotechnology

Recent advances in nanotechnology have allowed for the formulation of chitosan into nanoparticles, significantly improving its stability, delivery efficiency, and bioavailability. Chitosan nanoparticles (CNPs) have several advantages over bulk chitosan, such as improved adhesion to plant surfaces, controlled release of active components, deeper penetration into plant tissues, lower dosage requirements, and longer bioactivity (Saberi-Riseh *et al*., 2021). These nano-formulations can be loaded with agrochemicals, plant growth promoters, or bioagents, resulting in multifunctional delivery systems. For example, Trichoderma spores encapsulated in chitosan nanoparticles are more viable and can be delivered more precisely to the rhizosphere. Similarly, nano-chitosan formulations containing essential oils or micronutrients can both nourish and protect crops. Furthermore, CNPs have improved antimicrobial properties due to their larger surface area and increased interaction with microbial membranes, making them effective against a variety of pathogens such as Fusarium, Botrytis, and Pythium spp. This establishes nano-chitosan as a promising tool for precision agriculture and integrated pest management approaches.

Advantages and Limitations

Chitosan has emerged as a promising tool for sustainable agriculture due to its distinct biological properties and compatibility with ecological farming systems. Despite its numerous advantages, certain practical challenges still limit its widespread use in field conditions.

Advantages

Biodegradable and safe for the environment- One of the most significant benefits of chitosan is its biodegradability. Chitosan, which is derived from natural sources such as crustacean shells and fungal cell walls, decomposes harmlessly in the environment, making it a safer alternative to synthetic agrochemicals. It leaves no toxic residues and is consistent with eco-friendly farming principles (Maleki *et al*., 2020).

Broad-spectrum activity against pathogens- Chitosan has broad-spectrum antimicrobial properties, effectively inhibiting a diversity of fungal, viral, and bacterial pathogens. It works by disrupting microbial membranes, chelating essential nutrients, and activating plant immune responses, making it effective in a variety of crop-pathogen systems (Rabea *et al*., 2003).

Improves both local and systemic plant immunity- When chitosan is applied to a plant, it doesn't just strengthen the treated area—it also triggers defence responses throughout the entire plant. It activates two major immune pathways: the salicylic acid pathway linked to SAR and the jasmonic acid/ethylene pathway associated with ISR. This dual activation leads to the expression of defence genes, a surge in reactive oxygen species (ROS), and the production of antimicrobial substances such as phytoalexins and pathogenesis-related (PR) proteins. Together, these responses help the plant build a strong and coordinated defence against potential infections (Pieterse *et al*., 2014).

Acceptable with Natural and Integrated Disease Management.

Many countries approve the use of chitosan in ecofriendly agricultural system due to its non-toxic and natural origin. It works well in Integrated Disease Management systems, where it can be combined with biological control agents and low-impact chemical interventions to reduce pesticide loads and manage resistance development (El Hadrami *et al*., 2010).

Limitations

Efficacy varies depending on molecular characteristics and crop species

The biological activity of chitosan is strongly influenced by its degree of deacetylation and molecular weight. Variations in these physico-chemical properties can result in inconsistent elicitor performance across formulations. Furthermore, plant species and developmental stage influence chitosan responsiveness, compromising standardisation for large-scale applications (Maleki *et al*., 2020; Younes and Rinaudo, 2015).

Potential for inconsistent field performance due to ecological factors. While chitosan performs well under controlled conditions, its effectiveness in open field environments may be limited by temperature, UV radiation, humidity, soil pH, and microbial degradation. These external variables may affect chitosan's stability or interaction with plant tissues, potentially leading to varying efficacy (Hadwiger, 2013). As a result, further optimisation of formulation and application methods is required to ensure inline field success.

Conclusion and Future Prospects

Chitosan has emerged as a promising and environmentally conscious biopolymer with high potential for plant disease management. Its unique ability to induce plant innate immunity via SAR and ISR mechanisms makes it an important component in sustainable agriculture. Unlike traditional pesticides, chitosan acts as an elicitor, stimulating the plant's natural defence systems. Such mode of action not only reduces the likelihood of resistance development, but also promotes long-term and wide-spectrum protection against a broad spectrum of pathogens of plants (El Hadrami *et al*., 2010; Maleki *et al*., 2020). The combination of chitosan-based strategies with other biological tools, such as beneficial microbial species (e.g., Trichoderma, Bacillus subtilis) and nanotechnology (e.g., chitosan nanoparticles), boosts the efficacy of disease management programs. These synergistic approaches can improve chitosan delivery, stability, and activity under changing field conditions while remaining compatible with organic and integrated pest management (IPM) systems (Saberi-Riseh *et al*., 2021). The strategic incorporation of chitosan into sustainable crop protection frameworks has great potential for reducing chemical pesticide use, preserving agroecosystem health, and improving global security of food.

Reference

Agrawal, G. K., Rakwal, R., Jwa, N. S., & Agrawal, V. P. (2002). Signaling molecules and blast pathogen attack activates rice genes encoding pathogenesis-related proteins. Current Science, 82(5), 425–428.

Allan, C. R., & Hadwiger, L. A. (1979). The fungicidal effect of chitosan on fungi of varying cell wall composition. Experimental Mycology, 3(3), 285–287.

Amborabe, B. E., Bonmort, J., Fleurat-Lessard, P., & Roblin, G. (2008). Early events induced by chitosan on plant cells. Journal of Experimental Botany, 59(8), 2317–2324.

Bakker, P. A. H. M. (2014). Induced systemic resistance by beneficial microbes. Annual Review of Phytopathology, 52, 347–375.

Ben-Shalom, N., Ardi, R., Pinto, R., Aki, C., & Fallik, E. (2003). Controlling gray mould caused by Botrytis cinerea in cucumber plants by means of chitosan. Crop Protection, 22(2), 285–290.

Bitelli, M., Iriti, M., & Faoro, F. (2001). Chitosan-induced resistance in barley. Plant Biology, 3(6), 609–615.

Boller, T., & Felix, G. (2009). A renaissance of elicitors: Perception of microbe-associated molecular patterns and danger signals by pattern-recognition receptors. Annual Review of Plant Biology, 60, 379–406.

Chakraborty, M., Mahapatra, A., & Patra, S. (2008). Induction of resistance in tomato against Fusarium oxysporum f. sp. lycopersici using chitosan. Archives of Phytopathology and Plant Protection, 41(5), 387–395.

Croteau, R., Kutchan, T. M., & Lewis, N. G. (1987). Natural products (secondary metabolites). In Biochemistry and Molecular Biology of Plants (pp. 1250–1318).

De Oliveira, A. G., Ribeiro, S. F. F., Pastore, G. M., & de Melo, I. S. (2016). Chitosan as a resistance elicitor against Fusarium solani in soybeans. Pesticide Biochemistry and Physiology, 132, 13–19.

Doares, S. H., Syrovets, T., Weiler, E. W., & Ryan, C. A. (1995). Oligogalacturonides and chitosan activate plant defense genes through the octadecanoid pathway. Proceedings of the National Academy of Sciences, 92(10), 4095–4098.

El-Hassni, M., El Hadrami, A., Daayf, F., Barka, E. A., & El Hadrami, I. (2004). Chitosan enhances the defense responses of date palm against Fusarium oxysporum f. sp. albedinis. Phytopathologia Mediterranea, 43(1), 9–16.

El Hadrami, A., Adam, L. R., El Hadrami, I., & Daayf, F. (2010). Chitosan in plant protection. Marine Drugs, 8(4), 968–987.

Faoro, F., & Iriti, M. (2007). Cell death behind the scenes: The effects of chitosan on plant defense. Environmental and Experimental Botany, 60(1), 157–164.

Faoro, F., Iriti, M., & Maffi, D. (2008). Chitosan-treated barley shows reduced disease symptoms and altered expression of defense genes. European Journal of Plant Pathology, 120(2), 155–164.

Gerami, M., Majidian, P., Ghorbanpour, M., & Alipour, S. (2020). Exogenous melatonin and chitosan alleviate salt-induced oxidative stress in Stevia rebaudiana through improving antioxidant activity and secondary metabolite production. Scientia Horticulturae, 262, 109067.

Gill, S. S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiology and Biochemistry, 48(12), 909–930.

Gornik, K., Grzesik, M., & Romanowska-Duda, Z. (2008). The effect of chitosan on rooting of grapevine cuttings and on subsequent plant growth under drought and pathogen stress. Journal of Fruit and Ornamental Plant Research, 16, 333–343.

Hadwiger, L. A., & Beckman, J. M. (1980). Chitosan as a component of pea–Fusarium solani interactions. Plant Physiology, 66(2), 205–211.

Hadwiger, L. A. (2013). Multiple effects of chitosan on plant systems: Solid science or hype. Plant Science, 208, 42–49.

Hidangmayum, A., Dwivedi, P., Katiyar, D., & Hemantaranjan, A. (2019). Application of chitosan on plant responses with special reference to abiotic stress. Physiology and Molecular Biology of Plants, 25(2), 313–326.

Hu, X., Neill, S. J., & Cai, W. (2004). Chitosan induces rapid activation of MAP kinases in Arabidopsis via the oxidative burst. Journal of Plant Physiology, 161(3), 289–296.

Iriti, M., & Faoro, F. (2008). Abscisic acid in plant–pathogen interactions. Recent Patents on Biotechnology, 2(3), 167–174.

Iriti, M., Sironi, M., Gomarasca, S., & Faoro, F. (2006). Pathogenesis-related proteins induced in grapevine leaves by chitosan. Phytoparasitica, 34(3), 239–247.

Iriti, M., & Faoro, F. (2009). Chitosan as a MAMP, searching for a PRR. Plant Signaling & Behaviour, 4(1), 66–68.

Kashyap, P. L., Xiang, X., & Heiden, P. (2020). Chitosan nanoparticle-based delivery systems for sustainable agriculture. International Journal of Biological Macromolecules, 157, 494–509.

Kauss, H. (1985). Callose biosynthesis as a calcium-regulated process and possible relation to plant disease resistance. Plant Cell Environment, 8(2), 71–75.

Khan, W., Prithiviraj, B., & Smith, D. L. (2003). Chitosan and plant disease resistance. Bulletin-OILB SROP, 26(10), 305–311.

Kohle, H., Jeblick, W., Poten, F., Blaschek, W., & Kauss, H. (1985). Chitosan-elicited callose synthesis in soybean cells as a Ca^{2+}-dependent process. Plant Physiology, 77(3), 544–551.

Lafontaine, P. J., & Benhamou, N. (1996). Chitosan treatment: Induction of tyloses and accumulation of phenolic compounds in xylem tissues of tomato. Phytopathology, 86(5), 520–529.

Li, T., Liu, Y., Shi, L., & Zheng, Y. (2017). Effect of chitosan on metabolite profiles of tomato fruit during postharvest storage. Food Chemistry, 234, 139–148.

Lin, W., Hu, X., Zhang, W., & Rogers, W. J. (2005). Hydrogen peroxide mediates defence gene induction in Arabidopsis in response to chitosan. Plant Physiology and Biochemistry, 43(9), 893–901.

Lizama-Uc, M. M., Arjona-López, J. M., & Santana-Buzzy, N. (2007). Activation of MAPKs in response to chitosan and oligogalacturonides in banana leaves. Biologia Plantarum, 51(4), 647–651.

Maleki, S. S., Mohammadi, S., & Mirshekari, B. (2020). Chitosan: A sustainable elicitor in plant defense responses. Environmental and Sustainability Indicators, 6, 100036.

Petrov, V., Hille, J., Mueller-Roeber, B., & Gechev, T. S. (2015). ROS-mediated abiotic stress-induced programmed cell death in plants. Frontiers in Plant Science, 6, 69.

Pearce, R. B., & Ride, J. P. (1982). Chitosan as a component of induced resistance to Fusarium wilt in tomato. Physiological Plant Pathology, 21(3), 325–332.

Pieterse, C. M. J., Zamioudis, C., Berendsen, R. L., Weller, D. M., van Wees, S. C. M., & Younes, I., & Rinaudo, M. (2015). Chitin and chitosan preparation from marine sources: Structure, properties, and applications. Marine Drugs, 13(3), 1133–1174.

Pillai, C. K. S., Paul, W., & Sharma, C. P. (2009). Chitin and chitosan polymers: Chemistry, solubility, and fiber formation. Progress in Polymer Science, 34(7), 641–678.

Popp, J., Peto, K., & Nagy, J. (2013). Pesticide productivity and food security: A review. Agronomy for Sustainable Development, 33(1), 243–255.

Rabea, E. I., Badawy, M. E. T., Stevens, C. V., Smagghe, G., & Steurbaut, W. (2003). Chitosan as antimicrobial agent: Applications and mode of action. Biomacromolecules, 4(6), 1457–1465.

Rinaudo, M. (2006). Chitin and chitosan: Properties and applications. Progress in Polymer Science, 31(7), 603–632.

Romanazzi, G., Nigro, F., Ippolito, A., & Di Venere, D. (2002). Effects of preharvest chitosan treatments on postharvest storage of table grapes. Journal of Plant Pathology, 84(2), 123–129.

Romanazzi, G., Nigro, F., Ippolito, A., Di Venere, D., & Salerno, M. (2009). Effects of pre- and postharvest chitosan treatments to control storage grey mold of table grapes. Journal of Food Science, 67(5), 1862–1867.

Saberi-Riseh, R., Moradi-Pour, M., & Ghasempour, H. R. (2021). Nano chitosan: A promising plant growth stimulator and biocontrol agent. Carbohydrate Polymers, 261, 117904.

Sen, S., Venkatesh, J., Kang, C. H., & Park, Y. U. (2020). Redox signaling and MAP kinase cascades in plant abiotic stress responses. Frontiers in Plant Science, 11, 1127.

Sheikhalipour, M., Khoshgoftarmanesh, A. H., Niknam, V., & Morteza, E. (2021). Chitosan enhances antioxidant enzyme activities and photosynthetic pigments in strawberry under salt stress. Scientia Horticulturae, 281, 109987.

Vlot, A. C., Dempsey, D. A., & Klessig, D. F. (2009). Salicylic acid, a multifaceted hormone to combat disease. Annual Review of Phytopathology, 47, 177–206.

Walker-Simmons, M., Hadwiger, L. A., & Ryan, C. A. (1984). Hormonal regulation of plant disease resistance and protein synthesis. Science, 226(4680), 1420–1426.

Wang, M., Li, Q., & Duan, X. (2008). Chitosan oligosaccharide induces resistance to Tobacco mosaic virus in Nicotiana benthamiana and Arabidopsis thaliana. Plant Pathology, 57(3), 404–410.

Xing, K., Zhu, X., Peng, X., & Qin, S. (2015). Chitosan antimicrobial and eliciting properties for pest control in agriculture: A review. Agronomy for Sustainable Development, 35(2), 569–588.

Yin, H., Zhao, X., Du, Y., & Li, C. (2021). Foliar application of chitosan enhances resistance to Magnaporthe oryzae and improves growth in rice seedlings. Plant Physiology and Biochemistry, 159, 181–188.

Younes, I., & Rinaudo, M. (2015). Chitin and chitosan preparation from marine sources: Structure, properties, and applications. Marine Drugs, 13(3), 1133–1174.